

**Full Scale Studies on the Thermophilic
Anaerobic Digestion Process
Research Report No. 59**

**Research Program for the Abatement of Municipal Pollution
under Provisions of the Canada- Ontario Agreement
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FULL SCALE STUDIES ON THE
THERMOPHILIC ANAEROBIC DIGESTION PROCESS

by

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RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION UNDER THE
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ABSTRACT

A plant scale thermophilic anaerobic digestion study was conducted to assess the feasibility and performance and to provide economic guidelines for the process as compared with the conventional mesophilic system.

The study was conducted in four distinct phases; the first three at specific applied digester loadings, with the fourth and final phase studying the effect of shock loadings. A full scale mesophilic digestion system, operating on the same raw sludge feed, was used as a comparison.

The study proved full scale thermophilic digestion to be feasible and capable of sludge stabilization performance similar to the mesophilic control unit, but at more rigorous applied digester loading levels.

At equal digester loadings of $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{d}$) and retention times of approximately 25 days, the thermophilic and mesophilic units achieved similar overall volatile solids reductions of approximately 40%. The thermophilic system produced slightly more gas and greater microorganism destruction than the mesophilic control system, but the thermophilic digested sludge dewatering characteristics and supernatant liquor solids were inferior.

In the second and third phases of the study, at digester loadings of 0.14 and $0.20 \text{ lb VS/ft}^3/\text{day}$ ($2.2 - 3.2 \text{ kg/m}^3 \cdot \text{d}$), respectively, and associated sludge retention times of 13 and 7.5 days, the thermophilic unit continued to provide good overall solids reductions of approximately 40%. The related gas production rates were similar to those achieved in the control unit. The latter was operated at a constant loading of approximately $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{d}$) as it was not feasible to increase raw sludge feed rates. Digested sludge chemical, physical and bacteriological characteristics at the higher loadings were little changed from those seen during the first phase of the study.

The operating parameters of the two systems were similar, with the exception that the thermophilic primary digester pH and volatile acids levels were higher than those seen in the control unit, averaging 7.4 and 2600 mg/l respectively as opposed to 7.0 and 95 mg/l.

The quality of the gas from both systems was similar, averaging 65% methane, with the balance being carbon dioxide. In the thermophilic process, the gas quality remained constant throughout the range of applied digester loadings studied.

The final phase of the study showed that widely and frequently varying applied digester loadings had little effect upon the thermophilic process, which proved to be very flexible in producing a good all round performance under the range of shock loadings applied.

While no actual operating cost comparison was made between the two digestion systems, estimates of energy requirements based on the data obtained showed that requirements would be slightly greater for the thermophilic process. However, the magnitude of the increase was such that conversion of existing overloaded mesophilic systems to thermophilic operation would be feasible and acceptable in view of the likely benefits to be obtained.

RÉSUMÉ

Nous avons effectué une étude à l'échelle réelle de la digestion anaérobie thermophile afin d'en évaluer l'application et le rendement et d'en déterminer les paramètres économique comparativement à la digestion mésophile classique.

Cette recherche s'est déroulée en quatre étapes distinctes: les trois premières avec des charges d'alimentation déterminées, quatrième, avec des surcharges soudaines afin d'en étudier les effets. Un digesteur mésophile, alimenté avec le même type de boues fraîches, a servi de témoin.

L'étude a démontré la possibilité de réaliser la digestion thermophile; cette dernière permettrait en outre de stabiliser les boues tout aussi bien que la digestion mésophile moyennant, toutefois, un équilibre plus rigoureux de la charge.

Pour une charge de $0,08 \text{ lb/pi}^3/\text{j}$ ($1,3 \text{ kg/m}^3/\text{j}$) de matières solides volatiles (MSV) et un séjour d'environ 25 jours, les digesteurs thermophile et mésophile ont tous deux donné environ 40 p.100 moins de MSV dans l'ensemble. Le premier a produit un peu plus de gaz que le second et il a détruit un plus grand nombre de micro-organismes, mais les caractéristiques de déshydratation des boues et celles des matières solides de la liqueur surnageante étaient inférieures.

Pour ce qui est des deuxième et troisième étapes, où les charges respectives étaient de $0,14$ et $0,20 \text{ lb/pi}^3/\text{j}$ ($2,2$ et $3,2 \text{ kg/m}^3/\text{j}$) de MSV et le séjour de 13 et de 7,5 j respectivement, le digesteur thermophile a continué de réduire d'environ 40 p.100 les matières solides. La production de gaz accompagnant la digestion était semblable à celle observée dans le digesteur mésophile. Ce dernier recevait environ $0,08 \text{ lb/pi}^3/\text{j}$ ($1,3 \text{ kg/m}^3/\text{j}$) de MSV, charge qu'il a été impossible d'augmenter. Les caractéristiques chimiques, physiques et bactériologiques des boues digérées, aux charges supérieures, n'étaient pas très différentes de celles observées au cours de la première étape.

La paramètres de fonctionnement des deux digesteurs étaient semblables, sauf la concentration des acides volatils et du pH dans le digesteur thermophile primaire qui s'élevaient respectivement à 2600 mg/l et 7,4, comparativement à 95 mg/l et 7,0 dans l'appareil mésophile.

Les gaz issus des deux digesteurs contenaient, en moyenne, 65 p. 100 de méthane, le reste étant du dioxyde de carbone. Dans le procédé thermophile, la qualité des gaz est demeurée constante en dépit des charges variables.

L'étape finale de l'étude a servi à démontrer que des variations fréquentes et importantes de la charge n'affectent pas le rendement du procédé thermophile, qui demeure remarquablement constant.

Même si les coûts d'exploitation des deux digesteurs n'ont pas été comparés, les besoins énergétiques dérivés de nos données sembleraient un peu plus élevés pour le procédé thermophile. Toutefois, cette différence est minime; la conversion des digesteurs mésophiles surchargés, actuellement en place, en digesteurs thermophiles serait réalisable et acceptable en regard des avantages qui en découleraient.

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CONCLUSIONS

1. At a conventional digester loading of $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{day}$) and retention time of 26 days, the thermophilic process achieved an overall performance similar to the mesophilic control system operated at the same loadings and using the same raw feed sludge.
2. At higher applied loadings, up to $0.20 \text{ lb VS/ft}^3/\text{day}$ ($3.2 \text{ kg/m}^3 \cdot \text{day}$) and retention time of 7.5 days, the thermophilic digester continued to provide good overall performance with solids reduction levels being 95% of those attained in the initial loading phase. In contrast, the literature sources agree that such loadings, particularly the hydraulic loading, would result in a much more reduced level of performance in a mesophilic operation.
3. The chemical characteristics of the final digested mesophilic and thermophilic sludges appeared similar.
4. Supernatant liquor from the thermophilic operation contained approximately twice the solids concentration of the mesophilic liquor.
5. The specific gas production was similar for both processes, averaging $17.7 \text{ ft}^3/\text{lb}$ solids destroyed ($1.1 \text{ m}^3/\text{kg}$) for all phases of the thermophilic study and $16.0 \text{ ft}^3/\text{lb}$ ($1.0 \text{ m}^3/\text{kg}$) for the mesophilic control unit. The quality of the gases produced by both systems was similar, averaging 65% methane, with the balance being carbon dioxide.
6. Thermophilic digestion was an order of magnitude more effective than mesophilic digestion in reducing the number of organisms capable of growth at 35°C , while specific tests for parasites showed little difference between the processes.
7. Thermophilic primary digester pH levels were half a unit higher than those seen in the mesophilic system, while volatile acids concentrations were 25 times greater. Other digester operating indices were similar in the two systems.
8. Direct injection of steam to the thermophilic primary digester proved to be reliable, with minimal maintenance requirements.

9. Neither digestion process would produce adequate quantities of digester gas to satisfy all plant heating demands in winter operation, requiring supplemental heating by an external fuel source. At equal digester loadings of $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{day}$) and retention periods of 26 days, estimates showed the mesophilic system to produce 15% more excess heat in summer operation, and require 20% less supplemental heating in winter than the thermophilic system.
10. The immediate practical application of the thermophilic process is the conversion of existing overloaded mesophilic units where digestion performance is poor. The improved digestion which would be associated with the conversion would likely also include higher gas production rates than previously seen and render the thermophilic process economically attractive.

RECOMMENDATIONS

1. The thermophilic digestion process can be applied in existing plant operations where solids stabilization performance is compromised by organic or hydraulic overloading conditions.
2. Thermophilic anaerobic digestion should be considered as an alternative to the mesophilic process in future design and construction in view of the likely capital cost savings associated with the former.
3. Further research should be conducted upon the thermophilic digestion process to establish the upper loading limits. The research should preferably be conducted on a plant scale to provide experience and data on digester systems performances and operations at very high hydraulic loadings in addition to sludge stabilization performance. For example, gas drying, digester heating, and digested sludge removal techniques at ultra-high loadings would be of interest.
4. Investigations into the basic microbiology of the organisms responsible for digestion and definition of the rate limiting factor should be conducted with a view to increasing solids destruction performances and specific gas production rates, allowing enhancement of process economics and the possible creation of a real, supplemental energy source.

While the major objective in the design and operation of water pollution control plants is the production of high quality effluents through the removal of organic pollutants, attention must be paid to the considerable quantities of sludge produced in achieving this goal. The sludge requires some form of pretreatment prior to disposal. While numerous research studies have been conducted to determine the potential application of various unit processes and operations to sludge treatment and handling, higher capital and operating costs are invariably associated with other methods of sludge treatment than anaerobic digestion. As a result, conventional mesophilic anaerobic digestion continues to be practiced, and plant expansions continue to provide for this form of sludge stabilization.

In spite of this, little research work has been conducted to determine the maximum capabilities of anaerobic digestion systems. Through the use of thermophilic digestion, it may be possible to increase capacities or capabilities of existing anaerobic digesters, and reduce the capital costs associated with sludge stabilization in proposed treatment facilities. Most of the research studies conducted on thermophilic digestion have been laboratory scale investigations with only two full scale studies reported in the literature, both being conducted over two decades ago. Considering that one of these full scale studies suffered from inadequate mixing, there is thus little firm documentation on the relative merits of thermophilic compared with mesophilic digestion.

This research project was conducted to assess the feasibility, performance and economics of thermophilic digestion in stabilizing municipal wastewater sludges. Operation of a full scale, two-stage anaerobic digestion system under thermophilic conditions was monitored over a range of applied organic loadings using conventional digestion process parameters. Parallel operation of a full scale anaerobic digestion system operating under mesophilic conditions was also monitored.

The information obtained is directed towards establishing guidelines for the design and potential application of thermophilic digestion systems.

Although numerous research studies on thermophilic bacteria had been conducted prior to 1930, as documented by Hyde [1], investigation into thermophilic anaerobic digestion started at approximately this time. One of the earliest studies reported was by Rudolfs and Heukelkian [2] who concluded in a laboratory study that an appreciable reduction in time required for digestion could be achieved at temperatures of 45 - 55°C rather than 28°C. Some discussion on heating considerations for thermophilic digestion was also presented.

Additional laboratory studies conducted by Heukelekian et al., [3,4,5,6,7] dealt with the influence of temperature, seeding and reaction control on the thermophilic digestion process, as well as studying the feasibility of continuous thermophilic digestion. The most significant conclusions reached in these studies were that digestion is retarded at temperatures above 60°C and that a considerable increase in the rate of gasification is achieved through agitation of the digesting sludge. Heukelkian also concluded that a longer digestion time was required with the batch process than with the continuous digestion process.

Fair and Moore [8] reviewed published data to determine the effect of temperature on anaerobic digestion, concluding that 33°C was the optimum for mesophilic digestion, with 55°C being the optimum for thermophilic digestion.

The first full scale studies conducted on thermophilic digestion were reported by Fischer and Greene [9], and dealt with plant scale test work conducted in 1931 and in the period 1942-44. Although the studies seemed to suffer from inadequate mixing, one of the conclusions reached was that 60 - 75 percent more sludge could be digested in a thermophilic two-stage digestion system than in a two-stage mesophilic digestion system of equal size. Direct steam injection was successfully used for sludge heating, since the existing conventional hot water heating coils were not satisfactory for maintaining thermophilic temperatures during these studies.

The only other full scale thermophilic digestion study reported in the literature was conducted by Garber [10] and involved extensive studies conducted at a WPCP in Los Angeles. Although numerous conclusions

were reached, emphasis was placed on the markedly improved sludge filterability and dewatering characteristics.

In a laboratory study conducted by Heukelekian and Kaplovsky [6], it was concluded that microorganisms responsible for digestion at 50°C are different from mesophilic digestion microorganisms, and that bacteria responsible for thermophilic digestion of sewage sludge seem to fit the characterization of facultative thermophilic bacteria better than that of obligate thermophiles. However, it is interesting to note that these conclusions were made on the basis of gas production at various temperatures rather than through bacteriological examination techniques. Garder [10], in conducting full scale thermophilic digestion studies, observed that cocci types of microorganisms dominated mesophilic sludge while thermophilic sludge was characterized by rod-type organisms. He concluded that increased filter yields with thermophilically digested sludge were the result of the rod-shaped organisms not having gelatinous sheaths, compared to the gelatinous sheaths found on the cocci forms. Golueke [11], however, in conducting laboratory studies, found little difference in the types of bacteria present in sludges digesting from temperatures of 30°C to 65°C.

While most studies on thermophilic digestion have concluded that satisfactory performance with respect to sludge stabilization and gas production can be achieved under thermophilic conditions, Pohland and Bloodgood [12] observed generally poor performance in laboratory digestion studies conducted at 126°F and 140°F. Severe foaming, poor gasification and foul odors were all associated with their thermophilic digestion studies. These authors also described an interesting control parameter based upon the calculation of volatile acids salts concentration from volatile acids results, and the relationship of the salts to the alkalinity.

Baskerville and Gale [13] introduced a simple method for determining the filterability of digested sludges using an automatic electronic instrument.

Dague [14] and Dague, McKinney and Pfeffer [15] reported from practical studies and literature reviews that the rate-limiting factor

in anaerobic digestion is sludge retention time, with Hindin and Dunstan [16] conducting experiments corroborating this evidence.

Finney and Evans [17], however, reported that the rate-limiting factor is phase transfer of produced gases.

Malina [18] provided a useful literature review of thermophilic digestion with comments on seeding of, and chemical addition to, anaerobic digestion systems.

Sierp [19] conducted thermodynamical studies on the anaerobic digestion process, concluding that considerable quantities of heat were evolved during digestion, showing the biochemical reactions to be exothermic.

It can also be concluded from the literature, that during thermophilic digestion volatile acids concentrations are an order of magnitude greater than those associated with mesophilic operation.

In summary, the documented literature generally indicates that satisfactory anaerobic digestion can be achieved under thermophilic conditions; however, upper organic and hydraulic limits for both mesophilic and thermophilic digestion have been poorly defined and an overall assessment of the feasibility of full scale thermophilic digestion has not been made.

Selection of the full scale anaerobic digestion system for the experimental studies was based upon several criteria. These were that the facility should feature two-stage digestion, employ mechanical mixing, provide adequate sludge heating capacity for thermophilic operation, have available adequate quantities of raw sludge and be within reasonable distance of the MOE research facilities.

Several units were inspected with respect to these criteria, and while some fulfilled most of the demands, none satisfied raw sludge availability and heating requirements.

The digestion system of the Elmira WPCP was ultimately selected as the experimental facility as it met the basic requirements at least as well as the other units, and had the singular advantage of being out of use, obviating the upset of a routine plant operation.

Raw feed sludge could readily be obtained by trucking from the nearby Waterloo WPCP, and primary digester heating inadequacies overcome by using direct steam injection from a temporarily installed external steam generator.

The anaerobic digestion system at the Elmira WPCP is two-stage with domed, fixed steel roofs, mechanical mixing, and heated by an external heat exchanger. The digesters are 30 ft (9.1 m) inside diameter, 22 ft S.W.D. (6.7 m), and of approximately the same liquid volume of $15,550 \text{ ft}^3$ (440 m^3) or 97,000 Imp. gallons.

3.1 Sludge Heating System

Heat is supplied to the WPCP heat exchanger by a boiler with a 75 ft^2 (7 m^2) heating surface and a rated gross output of $12 \times 10^6 \text{ Btu/day}$ ($14.6 \times 10^4 \text{ W}$). The boiler also supplies building heat. The exchanger is located in the digester building and the boiler in the basement of the WPCP control building, about 70 ft (21.5 m) from the digesters. Hot water is supplied from the boiler to the exchanger and returned by a closed-loop underground piping system, as shown in the WPCP layout schematic drawing (Figure 1).

The boiler fuel supply system was extensively modified to provide automatic blending of natural gas with digester gas in the event

FIGURE 1 TOWN OF ELMIRA W. P. C. P.

that the pressure of the latter dropped below boiler requirements. The original fuel system required the supply of one gas or the other as opposed to a blended fuel, and also required manual selection of the fuel gas.

The heat exchanger is a Dorr-Oliver-Long, size 25, countercurrent spiral flow unit with a rated capacity of 4.8×10^6 Btu/day (5.9×10^4 W) at water inlet temperature of 155°F (68.3°C), a sludge inlet temperature of 90°F (32.2°C) and flows of 62.5 Imp. gpm ($0.28 \text{ m}^3/\text{min}$) sludge and 33.0 Imp. gpm ($0.15 \text{ m}^3/\text{min}$) water.

It was estimated by the calculations shown in Appendix I that about 12×10^6 Btu/day (14.6×10^4 W) would be required to meet sludge heating demands and digester heat losses concomitant with digester operation at high loadings in the thermophilic range of temperatures of $120 - 130^\circ\text{F}$ ($49 - 54^\circ\text{C}$). The heat exchanger was incapable of supplying the heat required during the higher digester loading phases of the study.

Additional sludge heating was achieved by steam injection from an external steam generator. A 15 HP (147 kW) Fulton model 15E vertical tubeless boiler was installed to provide steam. The unit had a rated output of 12.5×10^6 Btu/day (15.3×10^4 W) operating on No. 2 fuel oil at a consumption of 3.8 x Imp. gph (17.3 l/hr). The open-ended steam injection pipe was 1.5 inches (3.8 cm) in diameter with the open end feeding into a mixer draft tube 20 ft (6 m) below the digester liquid surface. The pipe was firmly located by welding at five points along its length. Two vacuum breaker valves were installed on the steam delivery system to prevent backsiphoning of sludge to the steam generator. An ion exchange water softener system was installed to pretreat the steam generator feed water. The generator, as supplied, featured automatic shutoff in the event of high or low water level, and low fuel level. The unit operated at a maximum pressure of 15 psig (103.4 kPag).

A Taylor temperature recorder/controller, model 76JMY33, was installed to automatically operate the boiler, and was seen to be capable of controlling the digester temperature to $\pm 2^\circ\text{F}$. The boiler, softener, temperature controller and ancillary equipment were housed in a 10 ft x 10 ft x 8 ft (3 m x 3 m x 2.4 m) galvanized steel building, modified to conform with current safety practices and regulations, and located adjacent to the primary digester. The building was foam insulated, heated and all water lines to and from the building heat traced and insulated.

The steam boiler was used as the primary heating source with the heat exchanger acting as a standby or supplementary system.

3.2 Primary Digester Mixing

The primary digester contents were mixed by two 550 V, 3 HP (2.2 kW), Dorr-Oliver-Long mechanical mixers capable of providing upflow or downflow mixing patterns. The mixers, located close to the surface of the sludge, were served by draft tubes extending to within 3 ft (0.9 m) of the digester bottom. Prior to the start of the study the mixers were fully overhauled.

3.3 Gas Collection System

Both digester roofs and all existing gas piping were pressure tested using nitrogen gas at 10 psig (68.9 kPag). The tests showed that most of the piping was in poor condition.

A new, more conveniently routed gas system was designed and installed using CSA approved Dupont Aldyl "A" polyethylene piping of 3 inch (7.5 cm) diameter. A gas meter was installed in the digester building basement to measure secondary digester gas production. Downstream from the meter, the primary and secondary gas lines were joined, with an underground common line feeding the blend to the control building basement where the total gas volume was metered.

The digester roofs were found to be in good condition. All valves, flame arresters, pressure regulators and manometers were dismantled, inspected and repaired and pressure tested after reassembly.

A water-cooled condenser was installed in the primary gas line water accumulator to provide increased moisture removal from the gas and to minimize condensation further downstream and the resultant fouling of metering equipment, pressure regulators, etc.

The water gas burner was also overhauled and modified to provide automatic ignition in the vent of a flame-out due, for example, to high wind velocities.

3.4 Sludge Handling System

As the raw sludge production of the Elmira WPCP was inadequate to serve the requirements of the study, sludge was transferred to the plant by truck from the nearby Waterloo WPCP. Sludge was then stored in one of

the Elmira WPCP primary clarifiers, with a blanket of four or five feet (1.2 - 1.5 m) generally being maintained. A small sewage flow was continued through the clarifier during the study, to prevent septic conditions occurring. Elmira WPCP raw sludge was also fed to the digesters. The quantities of Elmira sludge fed were insignificant with respect to the total sludge volume added, being in the region of 2000 - 3000 Imp. gal per week (910 - 1360 m³).

In general, this system worked satisfactorily for the duration of the study, although on occasion, and for various reasons, the supply of Waterloo WPCP sludge was limited or stopped, at which times digester loadings were reduced or the system "idled" until raw sludge deliveries returned to normal.

In accordance with currently accepted practice, digested sludge was hauled by truck for land disposal.

The considerable effort and expense made to repair and modify the digesters and the various systems was necessary to avoid having the studies' scope or flexibility limited by breakdowns or malfunctions in the equipment, and to provide data which were a reflection of the biological process and not a result of any particular system weakness or limitation.

It was planned to run four loading phases in all, each being an increment greater than that preceding until a loading of about 0.3 lb VS/ft³/day (4.8 kg/m³·d) was achieved, or where process failure occurred.

Initially, the system was operated at a primary digester loading of approximately 0.08 lb VS/ft³/day (1.28 kg/m³·d). This is a fairly typical digester loading in Ontario, and approximated that of the Waterloo WPCP system, affording good comparison between thermophilic and mesophilic operation at more or less equivalent loadings. The direct comparison between the Elmira thermophilic digestion results and those from the Waterloo WPCP mesophilic unit was considered valid, as both systems were receiving the same raw sludge as feed.

The Waterloo WPCP digestion system is two-stage with the primary digester having a fixed steel roof, mechanical mixing and 124,500 ft³ (3524 m³) capacity. The secondary unit has a floating roof, is unmixed and has a capacity of 117,000 ft³ (3312 m³).

In general, the operation and monitoring of the experimental thermophilic anaerobic digestion system followed currently common procedures.

Process analyses were conducted on-site and in the MOE main laboratories. Analyses were conducted in accordance with methods outlined in "Standard Methods for the Examination of Water and Wastewater". The Capillary Suction Time Test is described in the paper, "A Simple Automatic Instrument for Determining the Filtrability of Sewage Sludges", by Baskerville and Gale [13]. The on-site analyses were conducted three days per week on the raw sludge, primary and secondary digester sludges, and supernatant liquor. The analyses performed are shown in Table 1.

TABLE 1. WASTE SAMPLED AND ANALYSES PERFORMED

Sample	TS	TVS	pH	Alka- linity	Volatile Acids	ORP	Capillary Suction Time Test
Raw Sludge	x	x	x				x
Primary Sludge	x	x	x	x	x	x	x
Secondary Sludge	x	x	x			x	x
Supernatant Liquor	x	x	x				

FREQUENCY: Three times per week

Samples of all four streams were returned to the MOE main laboratory once a month for more involved analyses. These included BOD₅, nitrogen, heavy metals, phosphorus analyses and confirmatory testing of on-site analyses. Samples of the Waterloo WPCP digesters were also submitted for these analyses. Bacteriological examinations were frequently conducted on samples from the Elmira and Waterloo digesters to provide profiles of bacterial population, fate of pathogens and other differences between the thermophilic and mesophilic sludges.

Digester gas analyses were conducted on-site weekly. These were run on a Fisher Model 25V Gas Partitioner using the standard HMPA and molecular sieve chromatographic columns for digester gas analysis.

All gauges, manometers and meters were read daily. These included primary and secondary digester gas productions and pressures, main boiler and heat exchanger running times, heat exchanger inlet and outlet pressures and temperatures, steam generator running time and gallons of water used, and primary digester temperature from the recorder chart. Raw sludge and secondary digester temperatures were recorded on a less frequent basis.

Maintenance of equipment was conducted on a routine schedule of a frequency similar to other digesters in the Province. Specialized maintenance of the steam boiler was conducted in accordance with the manufacturer's suggested schedule. All drip traps, moisture accumulators and drains were serviced daily.

The primary purpose of the anaerobic digestion process is the stabilization of raw sewage sludges by biological degradation to produce a digested sludge capable of little further decomposition and which can be discharged to farmland without creating a nuisance or hazard in the environment. Ideally, the digested sludge should also dewater readily.

Although other parameters such as gas production and quality are important, it should be emphasized that they are a function of the basic biological reaction between organic solids and bacteria, and might therefore be considered of somewhat secondary interest.

While many reports on studies of anaerobic digestion have a tendency to stress a particular parameter, the present report presents a broad overall view or assessment of the performance and operation of the thermophilic digestion process from all the information obtained.

Data from the entire Elmira thermophilic digestion study for each performance parameter are presented graphically in Figures 2, 5, 6, 7 to provide continuity and ease of interpretation in comparing performance achieved at each loading phase.

Each data point on the graphs represents the average of results obtained during the associated time period which approximates the primary digester nominal retention time. For example, during Phase 1 the nominal retention time was almost one month, and all results obtained within this time are averaged and shown as one point on the graph to represent the performance achieved during that retention period.

For Phase 2, data points are twice as frequent, as the digester retention time was about half that of Phase 1.

Phases 3 and 4 results are plotted on a one-week basis, as digester retention times then were about a quarter or less of those during Phase 1.

To allow ready comparison with primary digester results, the overall digestion system performance is plotted on the same time base, although the overall retention times, when the secondary digester volume was included, were twice those of the primary digester alone.

The duration of each phase was a function of digester retention time, and of the time required to achieve steady-state conditions. It

was arbitrarily considered that at least four, and preferably six or more, digester retention periods at steady-state conditions were required to provide meaningful data to characterize and assess the performance at each loading phase.

The first phase, at an average sludge feed rate of approximately 4000 Imp. gpd ($18.0 \text{ m}^3/\text{d}$) for a loading of $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.28 \text{ kg/m}^3 \cdot \text{d}$) had a nominal 24 to 28 day retention time. This phase was started in February, 1974, and was continued for a period of 38 weeks, or 10 retention periods.

The second phase, at an average sludge feed rate of 7300 Imp. gpd ($33 \text{ m}^3/\text{d}$) for a digester loading of approximately $0.14 \text{ lb VS/ft}^3/\text{day}$ ($2.2 \text{ kg/m}^3 \cdot \text{d}$) had a nominal retention time of approximately 13 days, and was run for 28 weeks or about 15 retention periods.

The third phase, of 13,000 Imp. gpd sludge feed ($59 \text{ m}^3/\text{d}$) and a loading in the order of $0.20 \text{ lb VS/ft}^3/\text{day}$ ($3.2 \text{ kg/m}^3 \cdot \text{d}$) for a retention time of seven days, was run for nine weeks, or nine retention periods.

The fourth and final phase was run for a period of ten weeks. It was initially planned to run this phase at a loading of $0.3 \text{ lb VS/ft}^3/\text{day}$ ($4.8 \text{ kg/m}^3 \cdot \text{d}$) or to the point where process failure occurred. In practice, however, due to mechanical problems at the WPCP unassociated with but affecting the digestion study, these loadings were not achieved nor maintained for the significant periods of time necessary to fully characterize digester performance under steady-state conditions. The opportunity was therefore taken to use these last few weeks of the program to study the results of widely and frequently varying sludge feed rates on the digestion system and to obtain information on their shock load effects.

The Waterloo WPCP mesophilic digestion system was used as a control to provide a comparison between mesophilic and thermophilic digestion processes at loadings in the order of $0.08 \text{ VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{d}$) and similar sludge retention periods. Appendix 4 summarizes the averaged overall performances of the Waterloo and Elmira operations.

5.1 Raw Sludge Characteristics

Table 2 shows the characteristics of the Elmira and Waterloo WPCP raw feed sludges.

TABLE 2. ELMIRA THERMOPHILIC AND WATERLOO MESOPHILIC
DIGESTER RAW SLUDGE CHARACTERISTICS

		pH	TS	TVS
ELMIRA	Avg.	5.8	4.8%	63.2%
	Range	5.3 - 6.3	3.5 - 6.0%	55 - 70%
WATERLOO	Avg.	5.9	4.5%	63.8%
	Range	5.4 - 6.6	3.3 - 5.7%	58 - 68%

Elmira results are based upon all the data obtained during the study from composite samples of the feed to the digester. Data from the Waterloo WPCP mesophilic operation represent all results obtained during 1974. In the Elmira thermophilic operation, raw sludge pumping rates to the digesters were adjusted to provide as constant a loading as possible on occasions when raw sludge solids concentrations did vary appreciably from the norm.

It should be noted that phosphorus removal by means of FeCl_3 addition is in effect at the Waterloo WPCP and that the sludge fed to both digestion systems during the study included the portion contributed by the chemical treatment.

The results show that both raw sludges were very similar in quality, allowing air comparison between the Elmira WPCP thermophilic digester performance and that obtained from the Waterloo WPCP mesophilic operation.

Raw sludge pumping rates were frequently calibrated by the primary clarifier draw-down method.

5.2 Digester Loadings

Figure 2 illustrates primary digester loadings, volatile solids reductions, and overall volatile solids reductions versus time in weeks for the Elmira WPCP thermophilic operation.

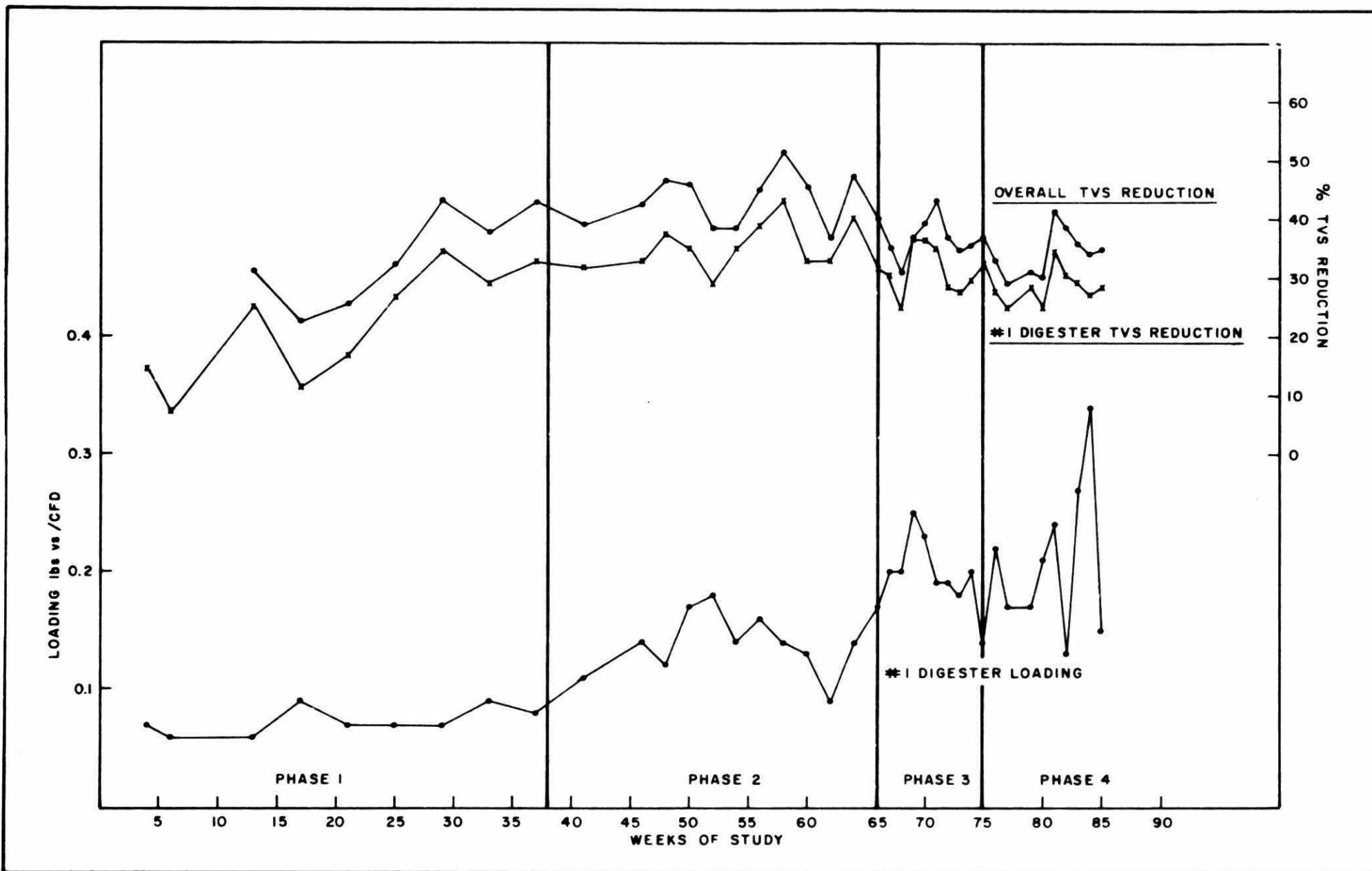


FIGURE 2 ELMIRA THERMOPHILIC DIGESTER SOLIDS REDUCTION PERFORMANCE AND PRIMARY DIGESTER LOADING

The vertical lines drawn at weeks 38, 66 and 75 indicate the end of each loading phase.

Table 3 shows the monthly and annual averages of digester loading with associated overall volatile solids reduction for the Waterloo WPCP mesophilic system.

TABLE 3. WATERLOO WPCP MESOPHILIC DIGESTER
LOADINGS AND VOLATILE SOLIDS REDUCTIONS

Month	Digester Loading lb VS/ft ³ /day (kg/m ³ ·d)		% TVS Reduction (overall)
1	0.07	(1.12)	42
2	0.09	(1.44)	-
3	0.10	(1.60)	-
4	0.09	(1.44)	52
5	0.06	(0.96)	39
6	-		-
7	0.07	(1.12)	36
8	0.08	(1.28)	41
9	0.05	(0.80)	30
10	0.08	(1.28)	42
11	-		-
12	0.09	(1.44)	35
Annual Avg.	0.08	(1.28)	40

For ready comparison with the Elmira WPCP digestion process, the Waterloo WPCP digester loading rates along with solids reduction and gas production performances are plotted in Figure 3.

The results from both digestion systems show that loadings varied appreciably even with careful monitoring of raw sludge solids concentrations and adjustment of sludge pumping rates applied.

This was likely due to the time lag between sampling the raw sludge and receiving the related analytical results. The time lag in the Elmira operation was usually about 27 hours.

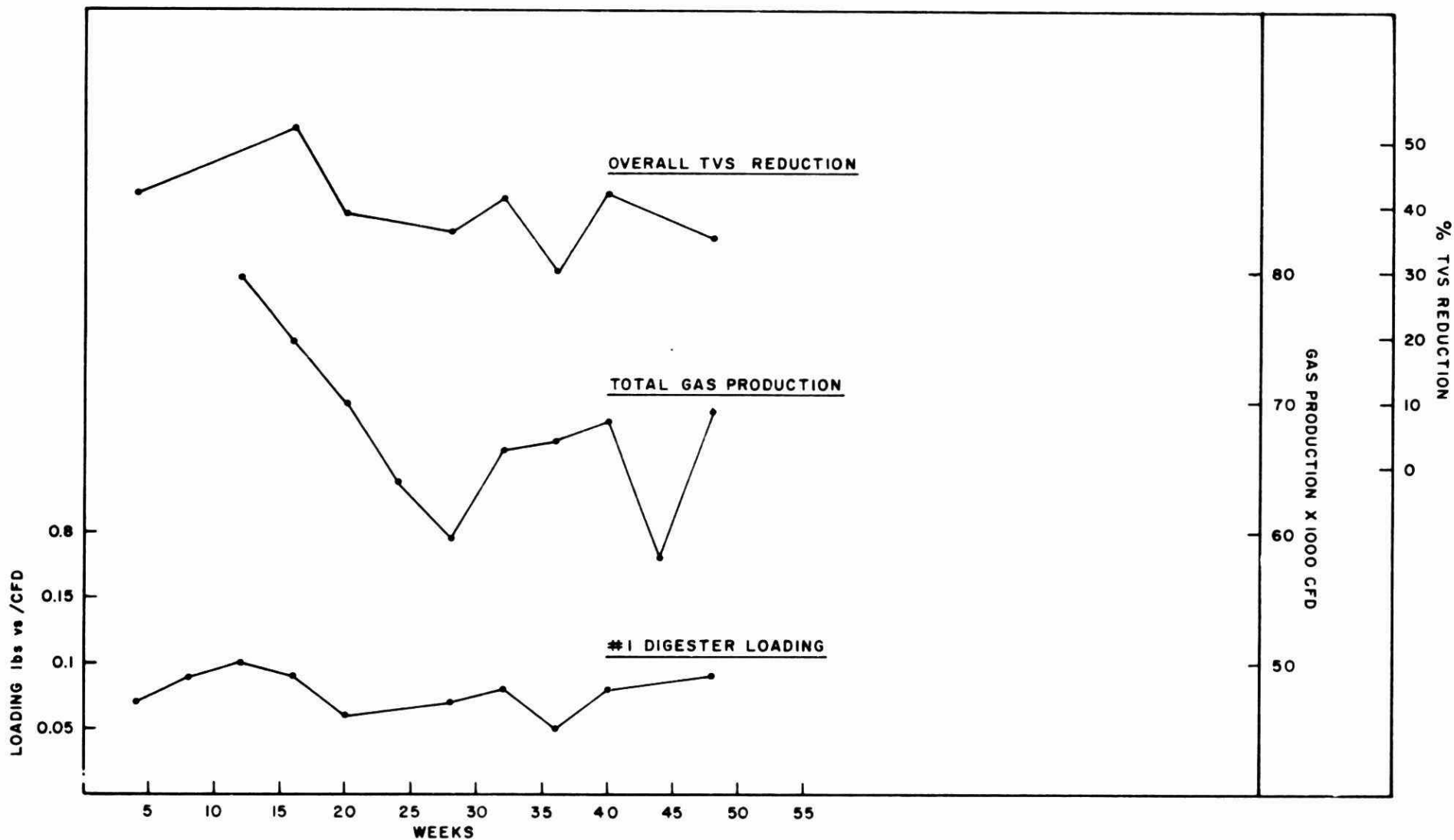


FIGURE 3 WATERLOO W.P.C.P. MESOPHILIC DIGESTER SOLIDS REDUCTION, GAS PRODUCTION AND DIGESTER LOADING FOR 1974

The difficulty in maintaining constant digester loadings is illustrated in Figure 2 for the Elmira operation, which shows the magnitude of digester loading variations for each nominal retention period.

While these comments apply to Phases 1, 2 and 3, the loading variations in Phase 4 were intentionally applied.

Figure 4 illustrates the relationship between digester loading and sludge retention time for the Elmira operation, assuming a constant solids concentration in the raw sludge. The curve is a rectangular hyperbola showing digester loading to be inversely proportional to sludge retention time.

It is likely that most full scale digestion systems experience day-to-day loading variations which will not be eliminated until a reliable, rapid, solids analysis technique is available, allowing almost instant compensating adjustment of raw sludge feed rates.

5.3 Volatile Solids Reduction

5.3.1 Comparison of Elmira thermophilic process with Waterloo mesophilic system

Table 4 summarizes the solids reduction performances and associated loadings of the Elmira and Waterloo WPCP digestion systems.

Phase 1 of the Elmira thermophilic study is directly comparable with the Waterloo mesophilic process as digester loadings and retention times were similar, with the units being fed the same feed sludge. In the Table, the Phase 1 results are based upon those obtained during weeks 25 - 38 of the study, inclusive, as that period was regarded as reflecting steady-state operation. Data obtained prior to week 25, while shown on Figures 2, 5, 6 and 7, are not included as bases of comparison with other Elmira loading phases nor the Waterloo mesophilic unit performance.

The results show that both digestion processes yielded similar overall volatile solids reduction performances under conditions of equal digester loadings, and similar sludge retention periods, with the only variable being temperature.

The volatile solids reduction performances achieved were in general agreement with those associated with two-stage mesophilic digestion systems serving conventional activated sludge plants [20].

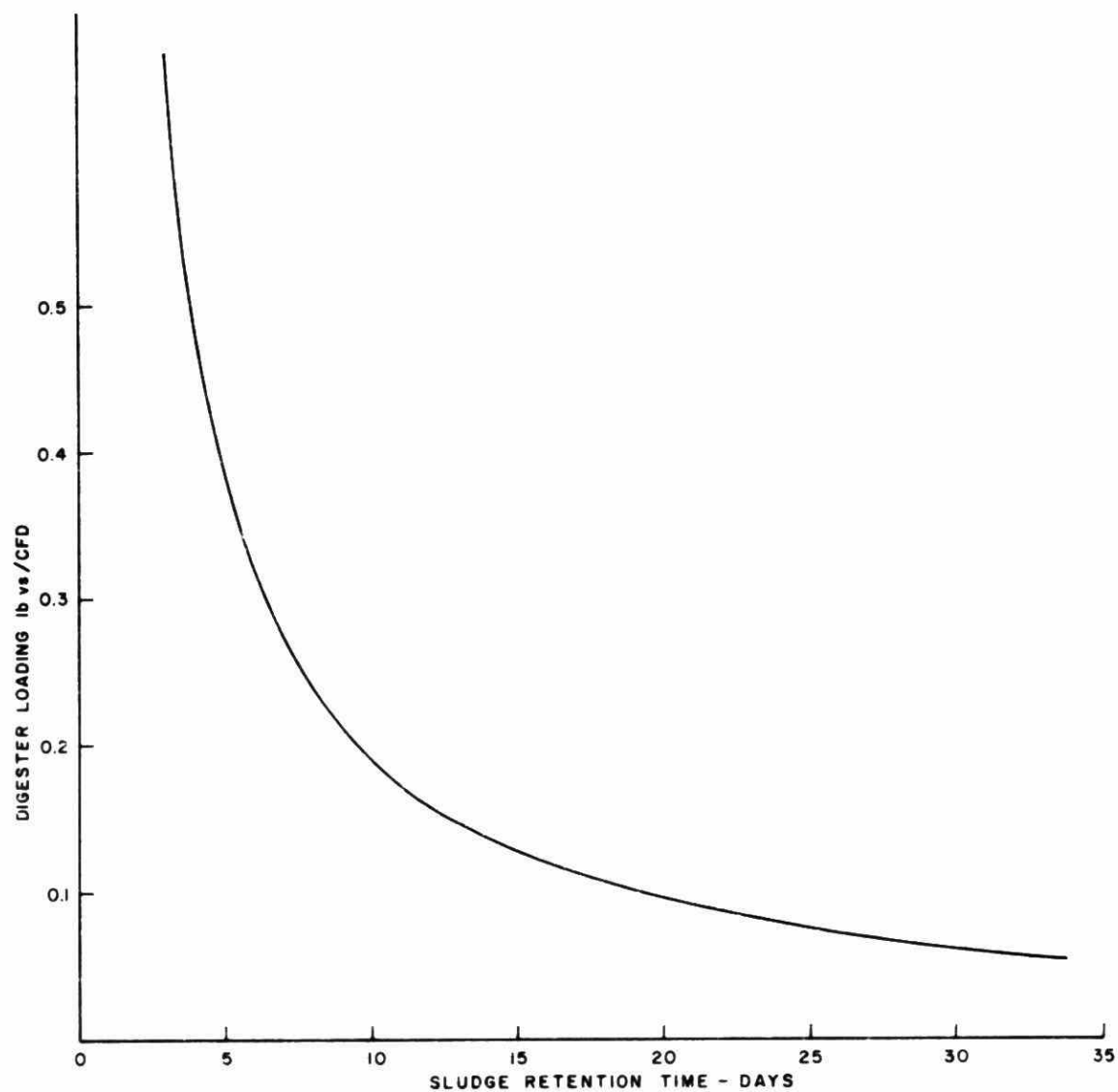


FIGURE 4 ELMIRA THERMOPHILIC DIGESTION STUDY RELATIONSHIP BETWEEN DIGESTER LOADING AND RETENTION TIME BASED UPON AVERAGE RAW SLUDGE CHARACTERISTICS OF 4.8% TS AND 63.2 % TVS

TABLE 4. SUMMARY OF THERMOPHILIC AND MESOPHILIC DIGESTER SOLIDS REDUCTION PERFORMANCES

	Average Loading lb VS/ft ³ /day	kg/m ³ ·d	Nominal Sludge Retention Time Days	Temp. °C °F		% TVS Reduction Avg. Max. Min.		
Elmira WPCP								
Thermophilic System								
Phase 1 Primary	0.08	1.3	26	54	130	31	34	29
Overall	-	-	-	-	-	39	49	33
Phase 2 Primary	0.14	2.2	13.3	54	129	35	44	29
Overall	-	-	-	-	-	43	56	37
Phase 3 Primary	0.20	3.2	7.5	53	128	31	37	25
Overall	-	-	-	-	-	37	43	31
Phase 4 Primary	0.13-0.34	2.1-5.4	5-10	51	124	28	34	25
Overall	-	-	-	-	-	34	42	29
Waterloo WPCP								
Mesophilic System								
Overall	0.08	1.3	23	33	91	40	52	30

5.3.2 Comparison of Elmira thermophilic study loading phases

The volatile solids reduction performances and digester loadings for all phases of the study are shown in Figure 2 and summarized in Table 4.

The Phase 2 solids reduction performance was 10% greater than that achieved during Phase 1, although the average digester loading was 75% greater with the sludge retention time being 50% shorter.

Phase 3 solids reduction performance was slightly inferior to that obtained during Phases 1 and 2. The general level of performance, however, was still acceptable by current standards.

During Phase 4, although digester loadings and retention times varied considerably, there was a 14-day period where they were fairly constant at $0.3 \text{ lb VS/ft}^3/\text{day}$ ($4.8 \text{ kg/m}^3 \cdot \text{d}$) and 5.7 days respectively. The average overall volatile solids reduction associated with this period was 35%.

These results, particularly those from Phases 3 and 4, suggest that while slightly reduced solids reduction performance is a function of digester loading and/or sludge retention time, there seems to be a considerable "reserve" digestion capability in the thermophilic system before process failure can be anticipated. As noted previously, Figure 4 shows that digester loadings were inversely proportional to sludge retention time, suggesting that if sludge retention is rate-limiting in the anaerobic digestion process, then very high digester loadings might be achieved before process failure occurs.

A comparison of the Elmira study results with those documented in the literature, indicates that performance of the thermophilic process is affected less than the mesophilic process by short sludge retention times.

Previous studies conducted on mesophilic digestion systems [14, 15, 16] indicated that solids reduction performance was massively and adversely affected by decreasing sludge retention time with 10 days being considered critical. Sludge retention time was considered rate-limiting with emphasis placed upon methanogenic bacteria regeneration rates being lower than bacteria "wash-out" rates at lower than normal sludge retention times.

While these studies showed solids destruction performances dropping rapidly in proportion with reduced retention times, the present thermophilic process study showed performance to be much less sensitive to changes in sludge retention time, with good performance being achieved at considerably less than 10 days retention.

A more recent study [17] suggests that the rate-limiting factor in the anaerobic digestion process is the phase transfer of the gases produced and that metabolic activity of the methanogenic bacteria is inhibited by dissolved product gases blocking substrate diffusion into intracellular sites. The report concludes that vigorous agitation, reduced pressures and elevated temperatures would speed the digestion process due to improved transport of dissolved gases to the gaseous phase.

It is therefore not clear whether the improved performance of the thermophilic process over the mesophilic system under high hydraulic loads is due to bacterial action or physical aspects of the system.

In summary, the Elmira WPCP thermophilic digestion process, Phase 1, achieved a volatile solids reduction performance of the same order as the Waterloo WPCP at similar hydraulic and organic loadings.

Phases 2 and 3 of the thermophilic study went on to produce acceptably good performances under much more stringent loading conditions. In Phase 3, at an average loading of $0.2 \text{ lb VS/ft}^3/\text{day}$ ($3.2 \text{ kg/m}^3 \cdot \text{d}$) and sludge retention time of 7.5 days, the overall solids reduction was 95% of that achieved under the more conventional loadings of Phase 1.

Brief operation of the thermophilic system at a sludge loading of $0.3 \text{ lb VS/ft}^3/\text{day}$ ($4.8 \text{ kg/m}^3 \cdot \text{d}$) and retention time of six days during Phase 4, yielded an overall solids reduction performance of 90% of that achieved in Phase 1.

Comparison of these data with those documented in the literature for mesophilic systems suggests that the thermophilic digestion process is markedly superior in resisting upset and producing good solids reduction performance under high organic and hydraulic loading conditions, although the mechanism allowing the improved performance is not clear.

Unfortunately, during the study, there was no opportunity to assess the maximum loading conditions possible before process failure occurred, but the data suggest that organic loadings in the order of

0.3 lb VS/ft³/day (4.8 kg/m³·d) and sludge retention times of five to six days or less would be feasible with the thermophilic digestion process. Based on documented literature, it is questionable if the mesophilic process would provide acceptable solids reduction performance at such digester loading levels.

5.4 Digested Sludge Characteristics

5.4.1 Chemical characteristics

Table 5 summarizes the quality of the digested sludge produced during the four phases of the Elmira thermophilic digestion study and the Waterloo WPCP mesophilic sludge characteristics.

In Elmira, over the duration of the study, the volume of digested sludge hauled for land disposal was 90% of the raw sludge feed to the digester, while at Waterloo the percentage was 88 for the year 1974, showing supernatant liquor discharges to the respective activated sludge sections to be minimal.

Comparing the results shows that there were no significant differences in chemical quality, and effects on land disposal sites should be very similar.

Subjectively, the color and odor of the thermophilic and mesophilic sludges was the same - black, with a not unpleasant, tarry odour. The thermophilic digested sludge appeared slightly more granular in physical appearance than the mesophilic sludge. Solids concentrations in both sludges were similar at around 2.8% TS.

5.4.2 Filterability tests

The filterabilities of the mesophilic and thermophilic digested sludges were determined by the Capillary Suction Time test (CST) [13]. Raw sludge CST was also measured.

The CST apparatus is a rapid, simple, electronic device employing a cell in which two sets of electrodes are in contact with chromatographic paper. Sludge is applied to the paper by a standard technique and as released water transports across the paper, contact is made with the first electrode which activates a digital timer. When the water has travelled a finite distance, the second electrode is contacted,

TABLE 5. THERMOPHILIC AND MESOPHILIC DIGESTED SLUDGE CHEMICAL QUALITY

Elmira Thermophilic Digester Phase	pH	TS %	TVS %	Zn	Cu	Ni	Pb mg/l	Cd	Cr	Mn	P		Nitrogen	
											Tot. mg/l	Sol. mg/l	Kjel mg/l	NH ₃ mg/l
1	7.4	3.1	50.3	65	49	4.1	15	0.6	20	10	1400	70	1440	1200
2	7.4	2.9	52.2	44	45	4.0	10	1.0	43	8	790	40	2550	680
3	7.6	2.9	51.5	120	62	3.0	15	0.9	25	9	1600	-	3000	950
4	7.7	2.8	52.8	48	30	1.6	7	1.1	19	6	740	30	2000	900
Waterloo Mesophilic Digester	7.4	2.8	52.0	30	40	3.9	10	0.6	-	7	640	-	2000	690

deactivating the timer. The displayed time, in seconds, is recorded as the CST time of the sample.

Table 6 shows the average CST results obtained in the study.

TABLE 6. DIGESTED SLUDGE FILTERABILITIES

Capillary Suction Time (Seconds)		
Raw Sludge		192 (4.7% TS)
Elmira Thermophilic Study	Primary Digester Sludge	Digested Sludge
Phase 1	885 (3.1% TS)	412 (3.1% TS)
Phase 2	936 (2.9% TS)	745 (2.9% TS)
Phase 3	679 (2.9% TS)	578 (2.9% TS)
Phase 4	650 (2.6% TS)	553 (2.8% TS)
Waterloo WPCP Mesophilic Digester	330 (2.8% TS)	255 (2.8% TS)

The percentages in brackets show the average total solids concentrations associated with the samples taken for the CST tests. No chemical conditioning was applied to the samples before testing.

The results show that the filterability of the thermophilic sludges was inferior at all times to the Waterloo WPCP mesophilic sludge. Spot checks on unconditioned mesophilic sludges from other digesters showed CST times in the region of 300 sec. proving the Waterloo sludge to be about average in filterability.

While these results agreed with the findings of a previous full scale study [9], the literature includes a report on another full scale study [10] where the opposite was the case.

Other laboratory scale tests [3, 4, 5, 6, 11] suggest improved filterability with thermophilically digested sludges.

In all these studies, however, chemical conditioning was applied before filterability measurements were made.

5.4.3 Bacteriological characteristics

Microbiological examinations were conducted over the term of the study to provide a comparison between the Waterloo WPCP mesophilic

sludge and the Elmira thermophilic sludge with respect to inactivation of pathogens and differences in microbial populations.

5.4.3.1 Waterloo WPCP mesophilic sludge. Microscopic examination showed a predominance of long chain bacteria, heavily encapsulated. Following selective culture, total coliforms, fecal coliforms and fecal streptococci, organisms used to indicate fecal "pollution", were isolated on all occasions. A Salmonella organism was isolated in one out of three of the samples examined. Salmonella were always found in the raw sludge.

In general, in these selective cultures, a variety of organisms typically found in human fecal material was isolated (proteus spp., pseudomonas spp. etc.), indicating that the digestion process had not been particularly destructive to organisms capable of growth in the intestinal tract.

The numbers of microorganisms capable of growth at 35°C were reduced by one to two orders of magnitude by mesophilic digestion. Most of the organisms in the raw and digested sludges appeared capable of growth under reduced oxygen tension, and at least 90% withstood heating to 65°C for thirty minutes.

In limited examinations for parasites, some ova from animal parasites were found, and were apparently viable.

5.4.3.2 Elmira thermophilic sludge. Microscopic examination showed the presence of encapsulated, predominantly short-chained bacteria. After selective culture, total coliforms and fecal coliforms were found, but no fecal streptococci or Salmonella types were isolated. Other organisms typically present in human fecal material were absent from these selective cultures.

The numbers of organisms capable of growth at 35°C were in general reduced by two to three orders of magnitude. Most of the organisms were able to grow under reduced oxygen tension, and could withstand a temperature of 65°C for thirty minutes.

Examination for parasites yielded results similar to those for mesophilic sludge.

In summary, microscopic examination revealed a qualitative difference between the sludges: the mesophilic sludge favouring the development of long-chain, heavily encapsulated types, the thermophilic sludge showing short-chain organisms encapsulated to a lesser degree.

The thermophilic digestion process yielded a greater overall reduction in microorganisms, and resulted in a much more efficient destruction of the organisms associated with the intestinal tract of man and animals.

In limited tests for parasites, little difference was seen between the two digestion processes.

5.5 Supernatant Liquor Quality

The Elmira WPCP thermophilic digester supernatant liquor characteristics are given in Table 7.

During the same period, the Waterloo WPCP mesophilic digester operation produced a supernatant liquor of 1.6% average total solids with the range being 0.4 - 2.5%.

Further analyses on the Waterloo supernatant liquor are not available.

The results show that the supernatant liquor from the thermophilic system was inferior to that from the mesophilic system with respect to solids levels.

Whether this is an intrinsic feature of the thermophilic digestion process or a function of the unusually high hydraulic loadings applied to the system during the study is not known, although the former is likely, as both systems had similar retention periods during the Elmira Phase I studies when that system still produced a poorer quality supernatant liquor than the Waterloo digester.

The importance of supernatant liquor quality is perhaps debatable, as in Ontario at least, discharges of the liquor to primary treatment and activated sludge systems are generally minimal in relation to overall sewage flows [20], representing very low if not insignificant additional pollutional loads on these systems.

TABLE 7. THERMOPHILIC SUPERNATANT LIQUOR QUALITY

Phase	pH	TS %	TVS %	BOD Unfilt/Filt mg/l	P		Free NH ₃ mg/l	Zn	Cu	Ni	Metals		Cr	Mn	Fe
					Tot. mg/l	Sol. mg/l					Pb mg/l	Cd mg/l			
1	7.4	2.5	55.4		463	52	1070	51	35	3.4	11	0.7	13	7.9	765
2	7.4	2.7	54.2	2225/320	600	52	930	32	54	3.6	11	0.9	40	6.0	-
3	7.6	2.9	55.6	2900/-	850	3	-	-	-	-	-	-	-	-	-
4	7.6	2.6	58.3	4000/-	520	34	900	46	27	1.7	7	1.0	15	5.0	-

5.6 Gas Production and Quality

5.6.1 Gas production

The average overall gas production and specific gas production rates along with other pertinent parameters are shown in Table 8 for the Elmira thermophilic and Waterloo mesophilic digestion systems.

In the table, Phase 1 results are based only on those obtained from weeks 25 to 38 of the study to reflect steady-state operation.

Figure 5 illustrates the Elmira thermophilic system primary digester and overall gas production rates and the methane content of the combined, or blended gases, the balance being carbon dioxide. Gas production rates were obtained from daily meter readings. While readings were made at 20°C, the values shown are corrected to STP (0°C and 760 mm). The methane content curve shows all the results obtained, while the gas production rate curve is based upon averaged results for each digester retention period. Figure 6 shows primary digester and overall specific gas production rates ($\text{ft}^3/\text{lb VS destroyed}$) for all four loading phases.

The Waterloo WPCP mesophilic digester overall gas production rate is illustrated in Figure 3 along with digester loading and solids reduction curves.

The results in Table 8 show that the specific gas productions achieved during the four phases of the thermophilic study were equal to, and sometimes slightly greater than those associated with the Waterloo mesophilic operation. A direct comparison between the thermophilic study Phase 1 and the Waterloo results, obtained at similar sludge loading and retention period conditions, shows that the thermophilic process produced 25% more gas per unit weight of volatile solids destroyed. Whether this was due to increased destruction of fats or greases or, as suggested earlier in the report, improved phase transfer of the product gases is not known.

Phases 2, 3 and 4 of the thermophilic study, while producing lower specific gas production rates than Phase 1, still equalled or surpassed the Waterloo mesophilic system performance despite considerably more rigorous operating conditions being applied.

TABLE 8. DIGESTER GAS PRODUCTION RATES

	Digester Loading		Retention Time	Volatile Solids Reduction	Gas Production		Specific Gas Production	
	lb VS/ft ³ /day (kg/m ³ ·d)		Days	%	ft ³ /day (m ³ /d)		ft ³ /lb VS Destroyed	(m ³ /kg)
Elmira Thermophilic Study								
Phase 1	0.08	(1.3)	26	39	9567	(271)	20.2	(1.25)
Phase 2	0.14	(2.2)	13	43	13987	(396)	16.0	(0.99)
Phase 3	0.20	(3.2)	7.5	37	18657	(528)	16.9	(1.06)
Phase 4	0.13-0.34	(2.1-5.4)	5-10	34	19579	(554)	18.4	(1.14)
Waterloo Mesophilic System								
	0.08	(1.3)	23	40	67491	(1910)	16.0	(0.99)

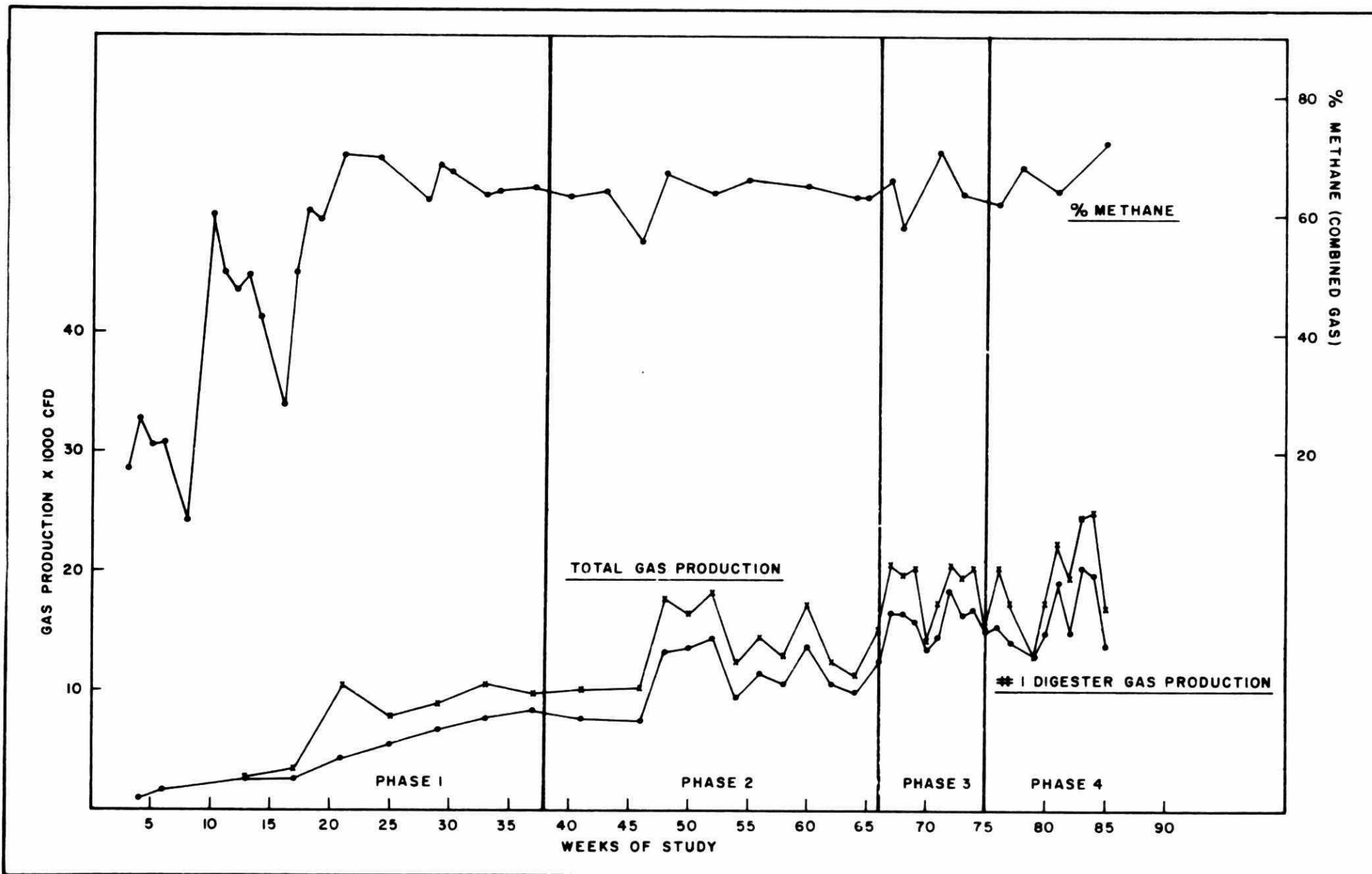


FIGURE 5 ELMIRA THERMOPHILIC DIGESTER GAS PRODUCTION RATES AND QUALITY

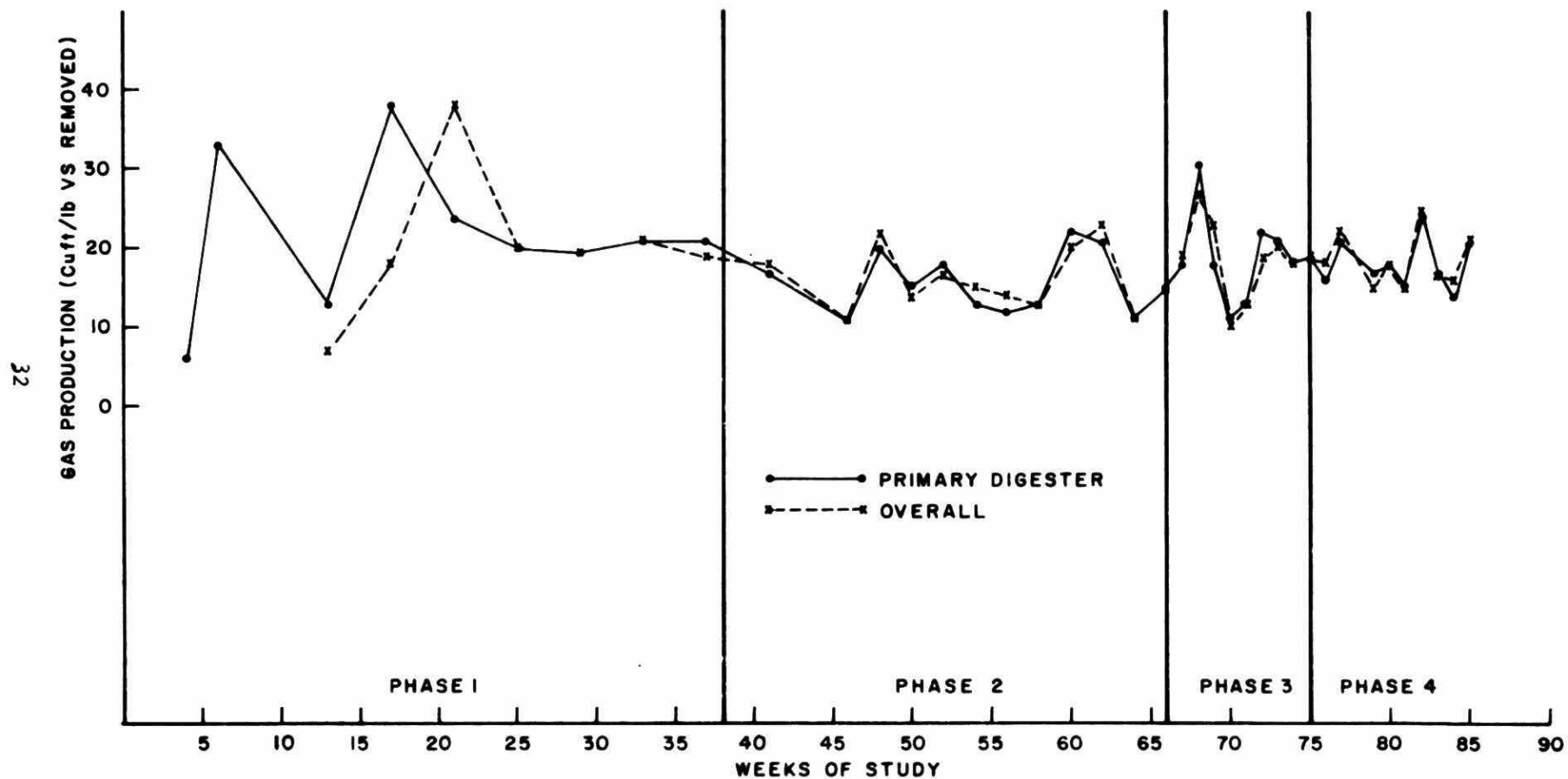


FIGURE 6 ELMIRA THERMOPHILIC DIGESTER SPECIFIC GAS PRODUCTION

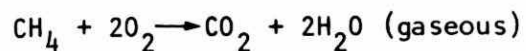
It might be noted that the gas production performance of the thermophilic digestion system was likely slightly greater than shown, as during the higher loading phases of the study some gas losses were experienced due to digested sludge haulage operations. This was occasioned by the need to provide secondary digester weekend storage capacity, thus minimizing supernatant discharge to the WPCP activated sludge system. In order to optimize the digestion operation and avoid disruption of other plant processes, it was necessary to remove digested sludge below the secondary digester water seal level, allowing some digester gas to escape to the atmosphere for periods up to an estimated four hours. This undesirable condition occurred one to three times per week and, during Phases 3 and 4 of the study, would represent a gas loss of about 3000 ft³/day (85 m³/d) or 16% on each day of the occurrence.

5.6.2 Gas quality

The quality of the gas produced by the thermophilic digestion system was good and quite stable after steady-state operation was achieved at about week 25 of the study. The primary and secondary digester gases were of more or less the same composition after the initial "start-up" stage of the study, and only the blended or combined gas analyses are shown on Figure 5. During the weeks immediately following digester start-up, considerable quantities of nitrogen were detected in the gas, but when the system attained a good steady-state level of general performance, the nitrogen content disappeared and did not recur.

The average methane content over the course of the study was 65%.

The net calorific value of methane, (lower heating value) saturated with water, at 15.5°C and 1.0 atmosphere pressure is 896 Btu/ft³ by the equation:



The thermophilic digester gas would therefore have an average calorific value of

$$896 \times \frac{65}{100} = 582 \text{ Btu/ft}^3 \text{ (21.5 MJ/m}^3\text{)}$$

Due to mechanical difficulties, the gas was not used to fuel the WPCP boiler, and was wasted by burning. The gas burned well at all times.

Occasional analyses of the Waterloo WPCP mesophilic digester gas showed an average methane content of 65%.

The specific gas production results shown in Table 8 are in general agreement with available literature. Golueke [11] reported similar gas yields between thermophilic and mesophilic digestion, with Fischer and Greene [9] showing slightly increased productions during thermophilic operation.

5.7 The Effect of Shock Loadings upon the Thermophilic Digestion Process

Phase 4 of the study was originally intended to examine digester performance at a steady-state loading of $0.3 \text{ lb VS/ft}^3/\text{day}$ ($4.8 \text{ kg/m}^3 \cdot \text{d}$). However, due to mechanical and electrical difficulties with the WPCP boiler, these higher loadings could not be constantly maintained due to lack of heating capacity from time to time, and the decision was taken to use the remaining time to study organic and hydraulic shock load effects upon the process.

During Phase 4, digester loading rates ranged between 0.13 and $0.34 \text{ lb VS/ft}^3/\text{day}$ (2.08 and $5.44 \text{ kg/m}^3 \cdot \text{d}$).

Figure 2 shows digester loading rates, primary digestion volatile solids reduction, and overall volatile solids reduction. The graph shows that while the solids reduction performance throughout the phase was not of the highest level, it was still comparable with other systems, particularly in view of the rather wide variations in applied digester loading rates and concomitant nominal sludge retention times.

Figure 5 shows that gas production rates and gas quality were good during the phase, equalling or bettering those observed during the other phases of the study.

Specific gas production rates, as shown on Figure 6 were also good, being comparable with those observed in previous phases.

Figure 7, showing the volatile acids salts-alkalinity relationship indicates a minor process inhibition during the first week of the

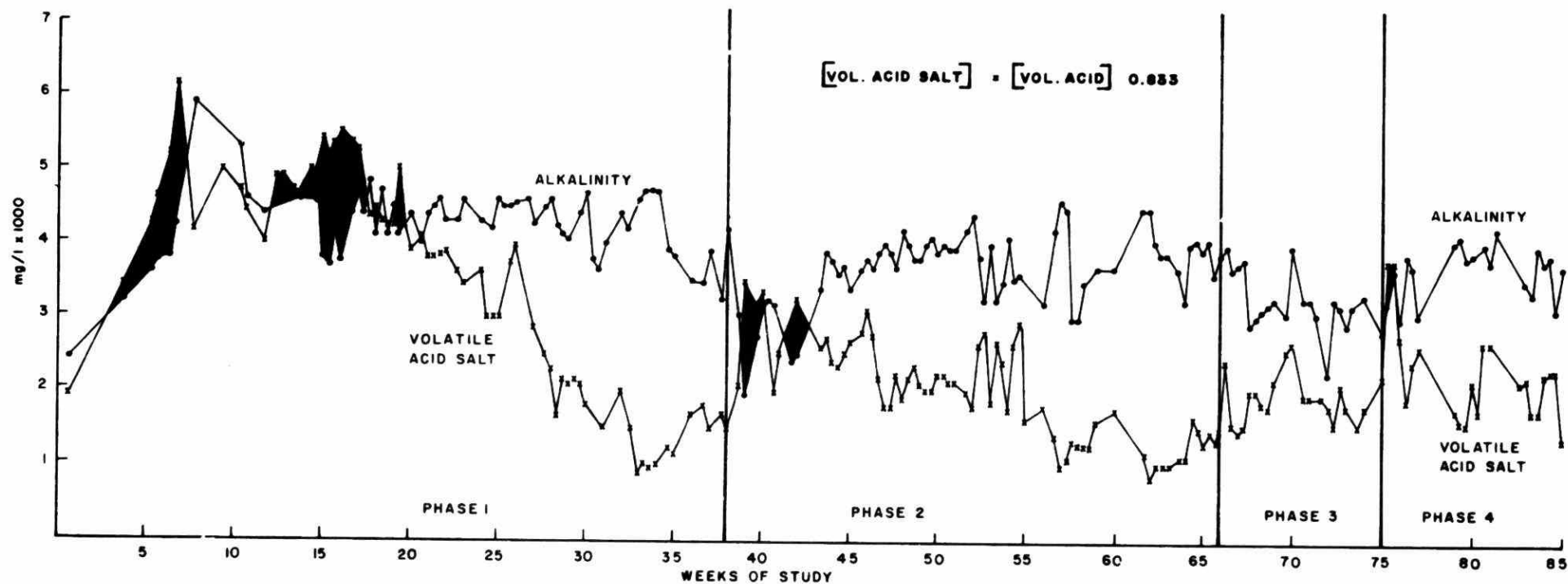


FIGURE 7 ELMIRA THERMOPHILIC DIGESTER STUDY VOLATILE ACID - ALKALINITY RELATIONSHIP

study, evidenced by the presence of free volatile acids. However, the process recovered quickly and went on to provide a good acids-alkalinity ratio which was not adversely affected by subsequent changes in the operating conditions.

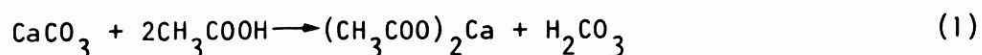
In general, the thermophilic digestion process was seen to be very capable of absorbing large changes in organic loading and sludge retention times. As the variation and frequency of conditions applied probably greatly exceeds those which might be associated with a steady-state WPCP operation, it would appear that the thermophilic digestion system would be unaffected to any appreciable degree by expected shock loads. The only qualification which might be made to the above conclusion is that large increases in hydraulic loading may inundate the system's heating equipment causing significant reductions in operating temperature with resultant inhibition of bacteria and corresponding decrease in digester performance, if not process failure.

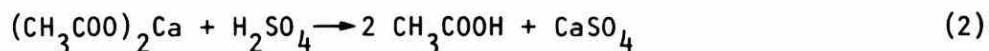
While the effect of rapid temperature changes was not examined during the study, every effort being made to maintain constant temperature, the literature suggests that rapid changes in the order of $\pm 5^{\circ}\text{F}$ per day may influence bacterial activity and reduce performance.

5.8 Primary Digester Operating Indices

While alkalinity and volatile acids are the major control parameters used in monitoring the anaerobic digestion process, a definite relationship between them had not been established until relatively recent times.

Pohland and Bloodgood [12] describe such a relationship based upon the concept of volatile acids salts. They show that during anaerobic decomposition of sewage sludge volatile acids and alkalinity are produced which react to form an acid salt with evolution of carbon dioxide. Subsequent biological degradation of the volatile acid salt again releases alkalinity to the process with production of methane, the cycle being repetitive. As the volatile acid salts react with acid, they appear as part of the alkalinity. The reactions may be expressed by:





The calculated quantity of apparent alkalinity contributed by the volatile acids salts with respect to the equations, can be obtained by multiplying the volatile acids concentration by a factor of 0.833.

In brief, where the volatile acids salts "alkalinity" exceeds total alkalinity a condition of free volatile acids presence would exist with no buffering potential remaining in the system. Associated decreases in pH and general impairment or cessation of biological digestion activity would then be anticipated.

Figure 7 shows alkalinity, and volatile acids salts values obtained during the thermophilic digestion study. The shaded areas indicate occasions of free volatile acids production. These occasions accompanied the period of digester start-up and those where digester loadings were rapidly increased, and were associated with general process inhibition as displayed by reductions in pH and gas production with occasional foaming in evidence.

Reference to Figure 5 shows that some reduction in primary digester gas production rates occurred simultaneously with the presence of free volatile acids. pH results provided more dramatic evidence of process upset during periods of free volatile acids production. At these times the pH of the sludge dropped to the range 6.2 - 6.5 from the normal range of 7.3 - 7.7.

Considerable foaming also accompanied the general disorders. This was controlled, although not cured, by the addition of antifoam emulsions.

When the volatile acids salts concentration dropped below that of the total alkalinity, all of the above symptoms rapidly disappeared and the process resumed normal operating characteristics.

Experience during the study showed that the volatile acids salts-alkalinity relationship is an excellent index for process control, being sensitive and quick to respond to variations in digestion conditions.

The relationship provided clear indications of impending process upset rather than merely showing that disruption had already occurred. Several times during the study, this feature was used to advantage with anticipated upsets being averted.

It was found that other indices such as pH and gas production rates were not particularly useful as process control tools, since these parameters were slower to respond to changes and usually appeared as process failure symptoms after the fact.

Clearly, pH will drop significantly when all process buffering potential has been depleted. At this time, the process may be considered as having failed and some time and effort would be required to attain normal conditions.

It should perhaps be stressed that increases in volatile acids concentrations, reductions in pH, and foaming are symptoms of process upset or failure and are not causative. The common causes of failure are likely due to overly rapid changes in the dynamics of bacterial populations caused by changes in the overall environment such as temperature and loading variations or inclusion of toxic compounds.

Other operating parameters monitored included digester sludge temperature, Oxidation Reduction Potential (ORP) and total and volatile solids. Table 9 summarizes the Elmira thermophilic and Waterloo mesophilic process results.

In agreement with documented literature, the volatile acids concentrations in the thermophilic process were much higher than those associated with the Waterloo mesophilic digestion system.

As noted earlier, the Elmira digester temperature was maintained within close limits by an automatic controller with day to day variations being small.

It is somewhat difficult to comment on the usefulness of the ORP measurement as an operating parameter as it was found to be sluggish in response to changes in digester conditions. Again, it is probably a parameter which would indicate process failure rather than provide "early warning" of an impending upset.

TABLE 9. PRIMARY DIGESTER OPERATING INDICES

	Avg. Loading lb VS/ft ³ /day (kg/m ³ ·d)	pH	Volatile Acids mg/l	Alkalinity mg/l	TS %	TVS %	ORP E _h	Temp. °F °C	
Elmira Thermophilic Process									
Phase 1	0.08 (1.3)	7.3	2400	4200	3.1	53.6	-488	129	54
Phase 2	0.14 (2.2)	7.3	2400	3600	2.9	55.5	-482	129	54
Phase 3	0.20 (3.2)	7.4	2400	3200	2.9	53.4	-558	128	53
Phase 4	variable	7.5	2700	3600	2.6	54.9	-535	124	51
Waterloo Mesophilic Process									
	0.08 (1.3)	7.0	95	4300	2.8	49.0	-522	91	33

While the major operating costs of the anaerobic digestion system are those associated with digester heating digested sludge disposal, the latter might be ignored in a comparison of thermophilic and mesophilic operations as the volumes of digested sludge for disposal would be the same for either process. Heating, therefore, is the major operating cost in a comparison of the two digestion processes.

Theoretical sludge heating requirements and digester heat losses as precalculated for the study are presented in Appendix 1.

During the study, data were collected to provide an actual evaluation of heating requirements. Results obtained for each phase of the study were averaged and are presented in Table 10.

TABLE 10. THERMOPHILIC DIGESTER HEAT BALANCE

Phase	Digester Temp.		Ambient Conditions	Sludge Heat Requirements		Heat Exchanger Input		Steam Generator Input		Digester Heat Loss	
	$^{\circ}\text{F}$	$^{\circ}\text{C}$		10^6 Btu/day		10^6 Btu/day		(10^4 W)		$(2+3)-(1)$	
				(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	129	54	Warm	2.7	(3.3)	2.2	(2.7)	1.5	(1.8)	1.0	(1.2)
	129	54	Cold	3.3	(4.0)	0.7	(0.9)	4.2	(5.1)	1.6	(2.0)
2	127	53	Warm	5.1	(6.2)	1.2	(1.5)	4.8	(5.9)	0.9	(1.1)
	129	54	Cold	5.2	(6.3)	1.1	(1.3)	5.8	(7.1)	1.6	(2.0)
3	128	53	Warm	8.0	(9.8)	3.1	(3.8)	5.7	(7.0)	0.8	(1.0)
4	124	51	Warm	7.9	(9.6)	3.0	(3.7)	5.8	(7.1)	0.9	(1.1)

Two sets of results are presented for Phases 1 and 2 as they embraced both winter and summer operation. The cold winter conditions were arbitrarily selected as the months from October to April inclusive, with the balance of the year being considered warm. The general range of ambient temperatures during the cold months is about -15 to 10°C while that for warm months is 10 to 35°C .

Heat exchanger input was calculated from manufacturer's specifications with 90% efficiency being assumed. Steam generator input was calculated as the difference between total water gallonage used and the quantities of steam vented during boiler blowdowns, drainings, etc.

In Appendix 1, it was calculated that digester heat losses would be 1.43×10^6 Btu/day (1.7×10^4 W) for cold weather operation, and 0.99×10^6 Btu/day (1.2×10^4 W) during warm ambient conditions for the digester with a noninsulated roof.

The actual results shown in Table 10 compare quite closely with the calculated values, although the raw data obtained cannot be considered to reflect absolute steady-state conditions due to ambient and digester temperature fluctuations. The latter, however, generally varied in the order of $\pm 0.5 - 1^\circ\text{F}$ from day to day, and were insignificant, while ambient variations were in the order of 30°F (17°C) daily.

The results suggest that actual digester heat losses were somewhat lower than the calculated values, as the latter were based upon a digester temperature of 125°F . As the actual digester operating temperatures were for the most part several degrees higher, it might be expected that concomitantly greater heat losses would be observed.

Few problems were associated with the digester heating systems.

The steam generator ran satisfactorily for almost 4000 hours with only three stoppages due to mechanical malfunctions. These were minor with two being due to faulty antisiphon valves, the other being a result of fouled water level control electrodes.

The quantity of water added to the digester by the generator was negligible, being at most 1000 gpd ($4.5 \text{ m}^3/\text{d}$).

In all, the performance of the steam generator was such that this type of equipment for general digester heating could be recommended, although no analyses have been made of the relative costs of pure steam heat and conventional heat exchangers.

While the WPCP heat exchanger and associated pumps proved reliable, the WPCP boiler failed several times during the study, on some occasions necessitating cutbacks in digester raw sludge feed rates to maintain digester temperature. These failures were unassociated with the thermophilic digestion study and were attributable to normal wear of various boiler control components.

The spiral heat exchanger performed satisfactorily with back-flushing being applied daily and cleaning when required. At no time was caking of sludge on the spirals observed, even when inlet water temperatures were maintained at 185°F (85°C).

In Section 5.6.2 it was observed that the digester gas produced during the study was not used to fuel the WPCP boiler due to mechanical difficulties. Table 11, however, shows a comparison of the heat required during the various phases of the thermophilic digestion study with the heat available from the product gas, and an appreciation of the extent to which the thermophilic digestion system would be self-sustaining with respect to digester energy demands.

The "total heat required" in the table includes digester heat losses in addition to sludge heating requirements, and is based upon observed values as opposed to those shown in Appendix I. Also included in the winter total heat requirements is the calculated quantity of heat required to satisfy building heat demands. This quantity was calculated by rule of thumb, based upon manufacturers' estimates of general building heat requirements. In sizing boilers it is generally assumed that building heat required is about 50% of the heat demands of a mesophilic digestion system at conventional loading levels. From Appendix II, based upon the Elmira WPCP, the additional heat required by the buildings in winter is approximately 1.7×10^6 Btu/day (2.1×10^4 W).

The "heat available from gas" in the table is based upon a gas heat content of 582 Btu/ft³ (21.5 MJ/m³).

The table shows that the thermophilic digestion system was heat deficient at all loadings during winter operation, requiring additional energy from an external fuel, while during summer operation, a small energy excess is seen, indicating the system to be self-sustaining with respect to heat demands. However, it should be noted that no account has been taken in these calculations for boiler and heat exchanger efficiencies, and that an additional external fuel supply could be required here also.

The Elmira WPCP heat exchanger alone would not satisfy thermophilic digester heating demands above a loading of 0.08 lb VS/ft³·day (1.3 kg/m³·d) in summer operation, and the plant boiler capacity would be marginal at a loading of 0.2 lb VS/ft³·day (3.2 kg/m³·d). Heating deficiencies of this

TABLE 11. ESTIMATE OF SUPPLEMENTAL HEAT REQUIREMENTS OF THE THERMOPHILIC DIGESTION SYSTEM

Digester Loading VS/ft ³ /day (kg/m ³ ·d)	Total Heat Required			Gas Production			Heat Available from Gas		Excess Heat Available			
	Winter		Summer						Winter		Summer	
	10 ⁶ Btu/day (10 ⁴ W)			ft ³ /day (m ³ /d)			10 ⁶ Btu/day (10 ⁴ W)		10 ⁶ Btu/day (10 ⁴ W)		10 ⁶ Btu/day (10 ⁴ W)	
0.08 (1.3)	6.6	(8.1)	3.6	(4.4)	9567	(271)	5.6	(6.8)	-1.0	(1.2)	+2.0	(2.4)
0.14 (2.2)	8.5	(10.4)	6.1	(7.4)	13987	(396)	8.1	(9.9)	-0.4	(0.5)	+2.0	(2.4)
0.20 (3.2)	12.0	(14.6)	9.0	(11.0)	18657	(528)	10.9	(13.3)	-1.1	(1.3)	+1.9	(2.3)

nature probably apply to other existing digestion systems where thermophilic operation is contemplated, although correction could be made quite simply by the installation of higher capacity exchangers or by using steam injection. Boiler outputs can likely be increased by modifications.

Table 12 shows a comparison of the estimated heat balance for thermophilic and mesophilic operation of the Elmira WPCP digestion system under winter and summer conditions at equal digester loadings.

The heat available from digester gas in the table is based upon the specific gas production rates observed during the study for the Elmira and Waterloo systems and shown in Section 5.5. The total heat required includes the raw sludge demand, digester heat loss and building heat during winter operation.

The table shows that thermophilic operation of the digester requires about 30% more heat than mesophilic operation under winter conditions, and about 90% more heat under summer conditions at the equal digester loadings of $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{d}$). It is also seen that neither system is self-sustaining in winter with respect to energy demands, and would be marginally self-sufficient in summer. No allowance has been made in the table for heat exchanger and boiler efficiencies.

Note that the quantity of supplementary heat required in winter operation and excess heat available during warm weather conditions was similar for both systems, showing that the costs associated with heating the thermophilic digester would be only slightly greater than those relating to mesophilic operation. The values in the table, however, as noted previously, were based upon the results achieved during the study, where the specific gas production of the thermophilic unit at the loading shown was $20.2 \text{ ft}^3/\text{lb}$ ($1.25 \text{ m}^3/\text{kg}$) as opposed to $16.0 \text{ ft}^3/\text{lb}$ ($0.99 \text{ m}^3/\text{kg}$) for the Waterloo mesophilic system. While these were the actual results obtained during the study, it is perhaps too speculative to suppose that they define the relative specific gas production performances of the two types of digestion systems at that loading as at other thermophilic digester loadings. Specific gas production rates more nearly approximate those achieved in the Waterloo control system.

In short, in the conversion of a mesophilic digestion system to thermophilic operation, where volatile solids reductions and specific gas

TABLE 12. COMPARISON OF THERMOPHILIC AND MESOPHILIC DIGESTION HEAT REQUIREMENTS

Digester Loading VS/ft ³ /day (kg/m ³ ·d)			Total Heat Required		Heat Available from Gas		Excess Heat	
			Thermophilic	Mesophilic	Thermophilic	Mesophilic	Thermophilic	Mesophilic
			10 ⁶ Btu/day (10 ⁴ W)		10 ⁶ Btu/day (10 ⁴ W)		10 ⁶ Btu/day (10 ⁴ W)	
0.08 (1.3)	Winter		6.6 (8.1)	5.0 (6.1)	5.6 (6.8)	4.2 (5.1)	-1.0 (1.2)	-0.8 (1.0)
	Summer		3.6 (4.4)	1.9 (2.3)	5.6 (6.8)	4.2 (5.1)	+2.0 (2.4)	+2.3 (2.8)

production rates were unchanged, the magnitude of the difference in supplemental heat required by thermophilic over that for mesophilic operation would be larger than the table shows. However, if such a conversion resulted in a greater volatile solids reduction performance, then overall gas production in the thermophilic system would be greater than for the mesophilic operation, and the economics of heating the thermophilic unit would be enhanced.

It is of note that there is no particular purpose in converting a well operating mesophilic digester to thermophilic operation, and that any likely conversions would be conducted on overloaded units producing presently poor levels of overall digestion performance. In these cases, thermophilic operation would most likely improve the solids reduction and allied overall gas production performances, which would tend to absorb the additional costs of heating the digester to the thermophilic range of temperatures.

No actual dollar value has been assigned to the estimates in this section as fuel cost rates depend on fuel type, rate of usage and vary with geographical region and time.

7.1 Application and Design of the Thermophilic Digestion Process

Perhaps the most immediate application of the thermophilic digestion process lies in the conversion of existing mesophilic systems which are overloaded organically or hydraulically or are approaching such conditions. Although the upper loading limits of the anaerobic digestion process are poorly defined in the literature, there is little doubt that the thermophilic process can be loaded to levels greater than the mesophilic digestion process. While the literature shows that the performance provided by mesophilic digestion processes drops rapidly as applied loading conditions are increased, the present study indicates that the thermophilic process is less affected by increased digestion demands, and will provide a good level of solids stabilization performance at loadings of $0.2 \text{ lb VS/ft}^3/\text{day}$ ($3.2 \text{ kg/m}^3 \cdot \text{d}$) or higher, and sludge retention times in the order of seven days.

The present study also shows no operational advantages in operating thermophilically in the region of $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.3 \text{ kg/m}^3 \cdot \text{d}$) as witnessed by the performance comparison between the Elmira thermophilic system and the Waterloo WPCP mesophilic system at that loading rate. It is probable that at digester loadings of about $0.15 \text{ lb VS/ft}^3/\text{day}$ ($2.4 \text{ kg/m}^3 \cdot \text{d}$) thermophilic operation of a digestion system may be desirable or even necessary to provide good overall digestion performance. Based upon the literature and the findings of this study, it appears that at digester loading rates of approximately $0.2 \text{ lb VS/ft}^3/\text{day}$ ($3.2 \text{ kg/m}^3 \cdot \text{d}$) or perhaps less, and sludge retention times of seven to ten days, thermophilic operation of a digestion system would be mandatory in providing an acceptably good level of performance with respect to all digestion parameters. While the energy requirements of an overloaded mesophilic system converted to thermophilic operation would increase slightly, the benefits to be gained would most likely outweigh a small additional operating expenditure.

If such a conversion of an existing system produced a higher volatile solids reduction performance with associated higher gas production rates, then the increase in digester heating costs would be minimized, if not totally absorbed, by the process itself.

Another application of the thermophilic digestion process would be the reduction of capital costs associated with new construction. This and other studies show that the thermophilic digestion process will provide good levels of general performance at loadings in the order of three to four times higher than those usually associated with mesophilic processes. This may be interpreted as meaning that a new digestion system designed solely for operation in the thermophilic range of temperatures could be considerably smaller in size than a conventional mesophilic unit. The cost savings associated with construction would therefore be significant, while mechanical services costs would be of the same order of magnitude as for a mesophilic unit.

While real estate costs are not normally a factor in digester construction, it is possible that savings could also be realized in this area. Of perhaps more significance than cost from a real estate or space point of view, is the availability of land in an existing treatment plant where expansion programs are proposed or projected. In at least one Ontario treatment plant, a digester system of rather unusually large height to diameter or aspect ratio has been built due to lack of available space. The design and construction of a thermophilic system would minimize such considerations as the unit could be much smaller.

The design of a thermophilic digestion system can follow normal procedures with some modifications. The major design difference from the conventional mesophilic system would be primary digester size or volume, as outlined earlier. It is probable that some of the cost savings resulting from the construction of a much smaller digester could be reinvested to increase insulating values over those presently found to further reduce digester heat losses and associated operating costs.

Boiler and heat exchanger sizes or capacities would be selected to satisfy all estimated heating requirements. More positive methods of moisture removal from digester gas than presently seen would be desirable.

Digested sludge removal techniques would be worthy of careful consideration. As noted elsewhere in the report, during the study some difficulties were experienced with sludge drawoffs allowing occasional loss of digester gas. A secondary digester with a floating roof may have

solved this problem. One method of minimizing problems associated with digested sludge drawoff might be the design of a thermophilic digestion system featuring a small primary digester followed by a conventionally sized secondary digester equipped with a floating roof.

Pumps, piping, mixers and other mechanical and electrical equipment would be sized in accordance with raw and digested sludge flow rates, characteristics, etc.

7.2 Advantages and Disadvantages of the Thermophilic Digestion Process

7.2.1 Advantages

The obvious major advantage of the thermophilic as compared with the mesophilic digestion process is the equivalent performance attainable at higher sludge loadings and shorter retention times than would be possible with the latter. It is also possible that the gas production per unit weight of volatile solids destroyed would be slightly higher in the thermophilic process.

The bacteriological quality of the thermophilic digested sludge is superior to that from the mesophilic process with respect to pathogen destruction.

In new construction, a thermophilic primary digester can be smaller than a conventionally sized mesophilic unit bringing savings in construction and possibly real estate costs. Such a small unit would likely produce lower heat losses, improving the economics of the system.

7.2.2 Disadvantages

There were two disadvantages associated with the thermophilic digestion process. The study showed digested sludge dewatering characteristics and supernatant quality to be inferior in the thermophilic system as compared with a mesophilic process. However, the effect of chemical conditioning on the digested sludge was not determined, and higher supernatant liquor solids concentrations might have been contributed to by higher than normal hydraulic loadings and greater secondary digester convection and produced gas mixing currents.

7.3 Frequency of Sampling

There are essentially two sets of parameters which may be applied to any treatment system. One set might be termed "performance"

parameters which would assess the performance of a system with respect to the extent of sludge stabilization provided. The other can be termed "operating" parameters which characterize the environmental conditions of the microorganisms responsible for waste treatment.

In anaerobic digestion, performance parameters would include raw, primary and digested sludge solids tests, gas production rates and quality, and chemical characteristics of digested sludge and supernatant liquor. The various streams associated with these parameters should be sampled at least once in every nominal retention period and preferably more often to fully and accurately assess digestion performance.

Operating parameters would basically include pH, volatile acids, alkalinity and any other tests pertinent to the particular operation.

To provide a method of predicting process upsets as described elsewhere in the report, alkalinity and volatile acids tests should be conducted at least twice a week as a frequency lower than that would not likely furnish adequate monitoring data and would be of little or no value.

7.4 Removal of Moisture from Digester Gas

In general, equipment installed for drying digester gas seems somewhat marginal, usually consisting of several drip traps and an "accumulator", the latter depending upon gas expansion cooling effects to condense water vapour.

While the standard installed gas drying equipment at the Elmira WPCP may be reasonably adequate for mesophilic digester operation at design loadings and associated gas production rates, it was found to be inadequate for drying the gas produced in the thermophilic study at all loading phases. The gas produced during the study, being at a considerably higher temperature than that from a mesophilic operation, contained considerably more water vapour than the latter, as the vapour pressure of water at 35°C is 42 mm and at 55°C is 118 mm.

In the study, it was found that during winter operations, little or no condensate was collected in the gas drying equipment, while summer operations produced considerable volumes, although still less than desired. This was likely due to the external sections of gas piping on the roofs behaving as condensers during cold weather and "refluxing" the

condensates back to the digesters, while in warmer weather this effect was minimized, placing greater demands on the drying equipment. To improve the moisture removal capabilities of the equipment, especially in summer operations, several modifications were made. These included the installation of a water-cooled condenser in the primary digester gas line water accumulator, and wrapping water-cooling coils around the pressure relief valve (PRV) on the roof and the sections of gas piping between the PRV and the accumulator.

Prior to the installation of additional cooling capacity, condensate had been observed as far downstream as the waste gas burner causing several "flame-outs", while after the modifications no further problems were encountered.

The removal of moisture from digester gas would be a very real concern in any plant contemplating conversion to a thermophilic digestion process, or in new construction, as it is likely that such systems would operate at digester loading levels considerably in excess of those associated with mesophilic operations, with attendant higher gas production rates. These higher gas flow rates alone, notwithstanding an increased moisture content, would likely inundate present moisture removal equipment designed for conventional loadings and gas flows.

Moisture removal from digester gas is an area largely ignored or minimized by design engineers to the detriment of the process and equipment. Experience in Ontario has shown the condensate to exert highly deleterious effects upon gas piping and other equipment occasioning considerable costs in repair or replacement, not to mention the digester "down-time" and man-hours involved. Much greater thought and attention should be paid to upgrading the design of moisture removal, and other digester systems as it appears that the anaerobic digestion process will be with us for some time to come.

Paradoxically, while engineers and operating personnel express concern over a few mg/l BOD in a WPCP final effluent, or a tenth of a pound difference in oxygen transferred by an aerator, somewhat more subdued reactions are reserved for the performances of digesters and their systems in general, giving the impression that the development of the process is being somewhat neglected.

While the research, design, process development and documentation of, for example, the activated sludge process in all its aspects is legion, there is a dearth of similar effort applied to the anaerobic digestion process with general knowledge and interest in the process falling short of that warranted. Digester mixing, heating, insulation, cleaning, and gas drying are some areas where much investigative effort could be applied.

7.5 The Mesophilic and Thermophilic Digestion Processes as Supplemental Energy Sources

From time to time, in an increasingly energy conscious age, the anaerobic digestion process is proposed as a supplemental source of energy in the form of produced methane gas.

Experiences in Ontario, including the present study, however, indicate that all or most of the energy produced, and usually then some, is required to maintain the anaerobic digestion process at operating temperature and also to supply building heat, at least in temperate climatic zones. While the reactions involved in anaerobic digestion are exothermic [19], the magnitude of the heat released in practice is rendered insignificant in view of the overall heat requirements of the mesophilic and thermophilic processes.

To provide energy in quantities far enough in excess of a plant's own heating requirements to warrant the likely capital and operating expenses of methane collection, purification and distribution, volatile solids reductions and particularly specific gas production rates would necessarily have to be increased to much higher levels than those commonly achieved at present. This would require extensive research of the basic microbiology of methanogenic bacteria in particular and the anaerobic digestion process and related systems in general.

Tables 11 and 12 provide an appreciation of the quantities of excess energy available in either thermophilic or mesophilic operation of the Elmira WPCP digestion system. As excess energy conditions are attained only in warm weather months with the magnitude of the excess being rather small, it is doubtful if it would be economically feasible to collect, process and distribute the excess gas. While these comments and observations apply to relatively small digesters in a temperate climate, a separate assessment or comment would be necessary for large, well-insulated units in lower latitudes.

7.6 Digestion Recovery Techniques in the Event of Process Inhibition or Failure

The addition of lime to digesters is a currently accepted practice on occasions of process upset or failure.

During the study, on occasion of a mild inhibition of the process when free volatile acids were in evidence and sludge pH had dropped to 6.6, lime was added to the primary digester in an attempt to raise the alkalinity and pH, and restore normal operating conditions.

The quantity of lime required to raise the pH of the sludge to 7.2 was determined by titration. In practice, a stoichiometric quantity of lime plus 20% was added. At this time, the raw sludge feed to the digester had been stopped. Intensive monitoring of pH, volatile acids and alkalinity conducted for forty-eight hours after the lime addition showed that the dosing had no effect upon the digestion conditions.

The addition of lime to anaerobic digestion processes has been somewhat controversial with some eminent authorities advocating the practice while others question it. Malina [18] provides information and references with respect to digester liming.

During the study, on other occasions of process upset or anticipated upset as indicated by the volatile acids salts-alkalinity relationship, it was found that the best procedure for restoring normal conditions consisted of halting raw sludge additions, accompanied by the return of secondary digested sludge to the primary digester.

During upsets, the quantity of secondary digested sludge returned generally equalled 5% of the primary digester volume per day. Experience showed that this technique would restore digester conditions to normal levels within twenty-four to forty-eight hours, when raw sludge additions could be resumed. During the increase in digester loading from Phase I to Phase II of the study, when the raw sludge feed rate was doubled and the process became inhibited, the technique was used extensively and appeared to hasten the recovery and acclimatization of the system to the new conditions.

In a multi-stage digestion system, the secondary, or digested sludge, is a readily available source of buffering potential and likely of methanobacter also. Literature indicates that these bacteria are more

susceptible to inhibition than the acid-forming bacteria, so that the return of digested sludge to an upset primary digester likely provides the twofold advantage of supplying additional buffering capacity, or alkalinity, and, perhaps more importantly, serving to maintain a good dynamic relationship between the acid and methane forming bacteria, thus hastening recovery by a more natural means than lime addition provides.

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APPENDIX 1

APPENDIX 1

ESTIMATE OF RAW SLUDGE HEATING REQUIREMENTS INCLUDING DIGESTER HEAT LOSS CALCULATIONS FOR OPERATION IN THE THERMOPHILIC RANGE OF TEMPERATURES

(Average Digester Operating Temperature 125°F (52°C))

It was projected that the study would begin with a digester loading of 0.07 lb VS/ft³/day (1.1 kg/m³·d) to form the first phase, and that loadings would be incrementally raised through several phases to a maximum of 0.3 lb VS/ft³/day (4.8 kg/m³·d) or to the point where the process failed, to complete the study.

The initial phase loading typified multistage digester loadings in the Province of Ontario, while the projected maximum loading of 0.3 lb VS/ft³/day (4.8 kg/m³·d) was about three times greater than the Provincial average and 50% greater than the highest recorded loading.

1. Sludge Heating Requirements

- a) At minimum digester loading of 0.07 lb VS/ft³/day (1.1 kg/m³·d).
Raw sludge average characteristics: 4% TS with 65% volatile fraction. Raw sludge feed for above loading:

$$= 0.07 \left(\frac{15550}{10} \times \frac{100}{4} \times \frac{100}{65} \right)$$
$$= 4186 \text{ lgpd (19 m}^3\text{/d)}$$

- i) Summer Conditions: Raw sludge temperature 60°F (15.5°C).
Heat required to raise sludge from 60°F (15.5°C) to 125°F (52°C) =

$$Q = mc \Delta t$$

where m = mass of sludge

c = thermal capacity (specific heat)

$$\Delta t = 65^\circ\text{F (36.5}^\circ\text{C)}$$

assuming c = 1.0

$$\text{then, } Q = (4.19 \times 10^3) 10 \times 65 \times 1.0$$
$$= 2.72 \times 10^6 \text{ Btu/day (3.3} \times 10^4\text{W)}$$

ii) Winter Conditions: Raw sludge temperature 35°F (1.7°C).

$$\begin{aligned}\text{Heat required, } Q &= (4.19 \times 10^3) 10 \times 90 \times 1.0 \\ &= 3.77 \times 10^6 \text{ Btu/day } (4.6 \times 10^4 \text{ W})\end{aligned}$$

b) At maximum digester loading of $0.3 \text{ lb VS/ft}^3/\text{day}$ ($4.8 \text{ kg/m}^3 \cdot \text{d}$).

Raw sludge feed for above loading:

$$\begin{aligned}&= 0.3 \left(\frac{15550}{10} \times \frac{100}{4} \times \frac{100}{65} \right) \\ &= 17942 \text{ lgpd } (81.4 \text{ m}^3/\text{day})\end{aligned}$$

i) Summer Conditions:

$$\begin{aligned}\text{Heat required, } Q &= (1.79 \times 10^4) 10 \times 65 \times 1.0 \\ &= 11.7 \times 10^6 \text{ Btu/day } (14.3 \times 10^4 \text{ W})\end{aligned}$$

ii) Winter Conditions:

$$\begin{aligned}\text{Heat required, } Q &= (1.79 \times 10^4) 10 \times 90 \times 1.0 \\ &= 16.1 \times 10^6 \text{ Btu/day } (19.6 \times 10^4 \text{ W})\end{aligned}$$

2. Digester Heat Losses

In calculating digester heat losses, various sections of the digester must be considered. There are:

- A (i) Roof with 4" foam insulation
- (ii) Roof with no insulation
- B Walls in air
- C Walls in earth
- D Floor in earth

A (i) Roof with 4" (10 cm) foam insulation:

Winter Operation: Average ambient temperature:

20°F (-7°C). (No correction applied for wind velocities)

ΔT : 105°F (59°C)

Roof area : 950 ft^2 (88 m^2)

Roof section: $0.5''$ (1.27 cm) steel; $4''$ (10 cm) foam

From Fourier's Law: $q = UA \Delta T$

where q = rate of heat flow

U = overall coefficient of heat transfer

A = surface area

ΔT = temperature gradient

$$\text{Now, } U = \frac{1}{\left(\frac{1}{h_f} + \frac{x}{k} + \frac{1}{h_g} \right) + \left(\frac{1}{h_{\text{air}}} + \frac{x}{k} \right)}$$

steel foam

where x = heat flow path
 k = thermal conductivity (average)
 h_f = fouling factor
 h_g = film coefficient of gas
 h_{air} = film coefficient of air

Therefore,

$$q = \frac{A \Delta T}{\left(\frac{1}{h_f} + \frac{x}{k} + \frac{1}{h_g} \right) + \left(\frac{1}{h_{\text{air}}} + \frac{x}{k} \right)}$$

steel foam

Therefore,

$$q_w = \frac{950 \times 105}{\left(\frac{1}{1000} + \frac{0.042}{26} + \frac{1}{10} \right) + \left(\frac{1}{0.2} + \frac{0.33}{0.02} \right)}$$

steel foam

$$= \frac{9.98 \times 10^4}{21.60} = 4.62 \times 10^3 \text{ Btu/hr (1.4 kw)}$$

Summer Operation: Average ambient temperature 70°F (21°C)
 $(\Delta t = 55^\circ\text{F})$

$$\text{then, } q_s = \frac{950 \times 55}{21.60}$$

$$= 2.42 \times 10^3 \text{ Btu/hr (0.7 kw)}$$

(ii) Noninsulated roof:

Winter Operation:

$$q_w = \frac{9.98 \times 10^4}{\left(\frac{1}{1000} + \frac{0.042}{26} + \frac{1}{10} + \frac{1}{0.2} \right)}$$

$(\Delta t = 105^\circ\text{F})$

$$= \frac{9.98 \times 10^4}{5.10} = 19.55 \times 10^3 \text{ Btu/hr (5.7 kw)}$$

Summer Operation:

$$q_s = \frac{5.23 \times 10^4}{5.10} = 10.24 \times 10^3 \text{ Btu/hr (3.0 kw)}$$

$(\Delta t = 55^\circ\text{F})$

B Walls in Air

Wall section: 1.5 ft (45 cm) concrete
2 in (5 cm) foamglass
4 in (10 cm) brick

$$\text{Wall area}_1 = 1151 \text{ ft}^2 (106.9 \text{ m}^2)$$

$$\text{Wall area}_2 = 305 \text{ ft}^2 (28.0 \text{ m}^2)$$

As 305 ft^2 of wall adjoins the digester pump room and is uninsulated, two separate heat loss values are calculated:

Winter Operation:

$$\begin{aligned} q_{w1} &= \frac{105 \times 1151}{\left(\frac{1.5}{0.7} + \frac{1}{2} + \frac{1}{1000}\right) + \left(\frac{0.17}{0.02}\right) + \left(\frac{0.33}{0.4} + \frac{1}{0.2}\right)} \\ (\Delta t = 105^\circ\text{F}) & \quad \text{concrete} \quad \text{foam} \quad \text{brick} \\ &= \frac{1.21 \times 10^5}{15.26} = 7.93 \times 10^3 \text{ Btu/hr (2.3 kw)} \end{aligned}$$

$$\begin{aligned} q_{w2} &= \frac{305 \times 65}{\left(\frac{1.5}{0.7} + \frac{1}{2} + \frac{1}{1000} + \frac{1}{0.2}\right)} \\ &= \frac{1.98 \times 10^4}{7.64} = 2.59 \times 10^3 \text{ Btu/hr (0.8 kw)} \end{aligned}$$

$$\text{total } q_w = q_{w1} + q_{w2} = 10.52 \times 10^3 \text{ Btu/hr (3.1 kw)}$$

Summer Operation:

$$\begin{aligned} q_{s1} &= \frac{1151 \times 55}{15.26} \\ (\Delta t = 55^\circ\text{F}) & \\ &= 4.15 \times 10^3 \text{ Btu/hr (1.2 kw)} \end{aligned}$$

$$\begin{aligned} q_{s2} &= \frac{305 \times 70}{7.64} \\ (\Delta t = 70^\circ\text{F}) & \\ &= 2.80 \times 10^3 \text{ Btu/hr (0.8 kw)} \end{aligned}$$

$$\text{total } q_s = q_{s1} + q_{s2} = 6.95 \times 10^3 \text{ Btu/hr (2.0 kw)}$$

C Walls in Earth:

Wall section: 1.5 ft concrete (45 cm)
2 in foamglass (5 cm)
4 in brick (10 cm)

$$\text{Wall area}_1 = 915 \text{ ft}^2 (85 \text{ m}^2)$$

$$\text{Wall area}_2 = 241 \text{ ft}^2 (22.4 \text{ m}^2)$$

In this section, 241 ft² of wall is adjacent to the pump room and is uninsulated necessitating two calculations for each condition.

Winter Operation:

$$\begin{aligned} q_{w1} &= \frac{75 \times 915}{\left(\frac{1.5}{0.7} + \frac{1}{1000} + \frac{1}{2}\right) + \left(\frac{0.17}{0.025}\right) + \left(\frac{0.33}{0.4} + \frac{1}{1}\right)} \\ (\Delta t = 75^\circ\text{F}) & \quad \text{concrete} \quad \text{glass} \quad \text{brick} \\ &= \frac{6.86 \times 10^4}{11.27} = 6.09 \times 10^3 \text{ Btu/hr (1.8 kw)} \end{aligned}$$

$$\begin{aligned} q_{w2} &= \frac{241 \times 65}{\left(\frac{1.5}{0.7} + \frac{1}{1000} + \frac{1}{1} + \frac{1}{2}\right)} = \frac{1.57 \times 10^4}{3.64} \\ (\Delta t = 65^\circ\text{F}) & \\ &= 4.3 \times 10^3 \text{ Btu/hr (1.3 kw)} \end{aligned}$$

$$\text{total } q_w = q_{w1} + q_{w2} = 10.39 \times 10^3 \text{ Btu/hr (3.1 kw)}$$

Summer Operation:

$$\begin{aligned} q_{s1} &= \frac{915 \times 60}{11.27} \\ (\Delta t = 60^\circ\text{F}) & \\ &= 4.87 \times 10^3 \text{ Btu/hr (1.4 kw)} \end{aligned}$$

$$\begin{aligned} q_{s2} &= \frac{241 \times 55}{3.64} \\ (\Delta t = 55^\circ\text{F}) & \\ &= 3.65 \times 10^3 \text{ Btu/hr (1.1 kw)} \end{aligned}$$

$$\text{total } q_s = q_{s1} + q_{s2} = 8.52 \times 10^3 \text{ Btu/hr (2.5 kw)}$$

D Floor in Earth:

Floor section: 1.5 ft concrete (45 cm)

Floor area: 804 ft² (75 m²)

Winter Operation:

$$q_w = \frac{804 \times 75}{\left(\frac{1.5}{0.7} + \frac{1}{2} + \frac{1}{2} + \frac{1}{1000}\right)}$$

($\Delta t = 75^\circ\text{F}$)

$$= \frac{6.03 \times 10^4}{3.14} = 1.92 \times 10^4 \text{ Btu/hr (5.6 kw)}$$

Summer Operation:

$$q_s = \frac{804 \times 60}{3.14}$$

($\Delta t = 60^\circ\text{F}$)

$$= 1.54 \times 10^4 \text{ Btu/hr (4.5 kw)}$$

E Total Digester Heat Loss at Thermophilic Operation Assuming 4 in (10 cm) Styrofoam Insulation of Roof

	<u>Winter</u>	<u>Summer</u>
Roof	4620	2420
Walls in Air	10520	6950
Walls in Earth	10390	8520
Floor in Earth	<u>19200</u>	<u>15400</u>
	TOTAL 44730 Btu/hr	TOTAL 33290 Btu/hr
	$\therefore q_w = 1.07 \times 10^6 \text{ Btu/day}$ (13.1 kw)	$\therefore q_s = 0.80 \times 10^6 \text{ Btu/day}$ (9.8 kw)

F Total Digester Heat Loss with Noninsulated Roof

	<u>Winter</u>	<u>Summer</u>
Roof	19550	10240
Walls in Air	10520	6950
Walls in Earth	10390	8520
Floor in Earth	<u>19200</u>	<u>15400</u>
	TOTAL 59660 Btu/hr	TOTAL 41110 Btu/hr
	$q_w = 1.43 \times 10^6 \text{ Btu/day}$ (17.5 kw)	$q_s = 0.99 \times 10^6 \text{ Btu/day}$ (12.1 kw)

Under the most rigorous operating conditions envisaged, maximum digester loading applied under winter conditions, the total digester heat demands would be the sum of sludge heat requirements plus digester heat losses with a noninsulated roof.

$$\begin{aligned} \text{i.e. } & 1 b(ii) + 2 F (q_w) \\ \text{or } & (16.10 \times 10^6) + (1.43 \times 10^6) = 17.53 \times 10^6 \text{ Btu/day (214 kw)} \end{aligned}$$

As the theoretical heat available, 12.5×10^6 Btu/day (153 kw) from the steam boiler and 4.8×10^6 (59 kw) from the heat exchanger for a total of 17.3×10^6 Btu/day (212 kw) approximated the calculated total heat demand under the most extreme conditions projected, i.e. with maximum load applied in winter, insulation of the digester roof was deemed unnecessary, particularly as the high digester loading phases of the study would be applied during warm weather conditions when heat demands would be minimized to a total of approximately 13×10^6 Btu/day (159 kw).

APPENDIX 2

APPENDIX 2

CALCULATION OF HEAT EXCHANGER INLET WATER TEMPERATURE REQUIRED TO HEAT SLUDGE TO 54°C (130°F)

Manufacturer's specifications for the WPCP heat exchanger are as shown:

Surface Area ft ²	Rated Capacity Btu/hr	Flow IGPM		Heat Loss ft		Temperature - °F			
		Sludge	Water	Sludge	Water	Sludge		Water	
In	Out	In	Out	In	Out	In	Out	In	Out
25	2 x 10 ⁵	62	33	5	5	90	95.3	155	145

A calculation was made to determine the inlet water temperature required to achieve sludge of 54°C (130°F) leaving the exchanger.

$$q = UA \bar{\Delta T}_L$$

where q = heat flow, Btu/hr (W)

U = overall coefficient of heat transfer

$$\frac{\text{Btu/hr}}{\text{ft}^2/^{\circ}\text{F}} \quad \left(\frac{\text{W}}{\text{m}^2/^{\circ}\text{C}} \right)$$

A = surface area of heat exchanger
ft² (m²)

$\bar{\Delta T}_L$ = log mean temperature difference

(In the calculation, the arithmetic mean was considered adequate)

Using the manufacturer's values for the exchanger:

$$2 \times 10^5 = U \times 25 \times 59.7$$

$$\begin{aligned} \therefore U &= \frac{2 \times 10^5}{25 \times 59.7} = \frac{2 \times 10^5}{1492} \\ &= 134 \frac{\text{Btu/hr}}{\text{ft}^2/^{\circ}\text{F}} \quad \left(\frac{761 \text{ W}}{\text{m}^2/^{\circ}\text{C}} \right) \end{aligned}$$

Letting T_{ha} = temperature of inlet water, and 54°C (130°F) the desired sludge temperature, then:

$$2 \times 10^5 = 134 \times 25 \times (T_{ha} - 130)$$

$$T_{ha} = \left(\frac{2 \times 10^5}{134 \times 25} \right) + 130$$

$$= 189.7^{\circ}\text{F} \text{ (} 88^{\circ}\text{C)}$$

APPENDIX 3

APPENDIX 3

DIGESTER HEAT LOSS AT THE MESOPHILIC RANGE OF TEMPERATURES

1. Sludge Heating Requirements

Digester Loading: $0.08 \text{ lb VS/ft}^3/\text{day}$ ($1.28 \text{ kg/m}^3 \cdot \text{d}$)

Raw sludge feed for above loading = 4000 lgpd ($18.1 \text{ m}^3/\text{d}$)

a) Summer Operation

Digester operating temperature 95°F (35°C)

Raw sludge temperature = 60°F (15.5°C)

Heat required, $Q = mc \Delta t$

$$= (4 \times 10^3) 10 \times 35 \times 1.0$$

$$= 1.4 \times 10^6 \text{ Btu/day (17.1 kw)}$$

b) Winter Operation

Raw sludge temperature 35°F (1.7°C)

$$Q = (4 \times 10^3) 10 \times 60 \times 1.0$$

$$= 2.4 \times 10^6 \text{ Btu/day (29.3 kw)}$$

2. Digester Heat Loss (Noninsulated roof)

a) Roof (i) summer operation - ambient temperature 70°F (21°C)

$$q_s = \frac{2.38 \times 10^4}{5.1} = 4.66 \times 10^3 \text{ Btu/hr (1.4 kw)}$$

($\Delta t = 25^\circ\text{F}$)

(ii) winter operation - ambient temperature 20°F (-7°C)

$$q_w = \frac{7.13 \times 10^4}{5.1} = 13.97 \times 10^3 \text{ Btu/hr (4.1 kw)}$$

($\Delta t = 75^\circ\text{F}$)

b) Walls in Air

(i) Summer Operation

$$q_{s1} = \frac{2.88 \times 10^4}{15.26} = 1.89 \times 10^3 \text{ Btu/hr (0.6 kw)}$$

($\Delta t = 25^\circ\text{F}$)

$$q_{s2} = \frac{1.22 \times 10^4}{7.64} = 1.60 \times 10^3 \text{ Btu/hr (0.5 kw)}$$

($\Delta t = 40^\circ\text{F}$)

Total $q_s = 3.49 \times 10^3 \text{ Btu/hr (1.0 kw)}$

(ii) Winter Operation

$$q_{w1} = \frac{8.63 \times 10^4}{15.26} = 5.66 \times 10^3 \text{ Btu/hr (1.7 kw)}$$

$$(\Delta t = 75^\circ\text{F})$$

$$q_{w2} = \frac{1.07 \times 10^4}{7.64} = 1.40 \times 10^3 \text{ Btu/hr (0.4 kw)}$$

$$(\Delta t = 35^\circ\text{F})$$

$$\text{Total } q_w = 7.06 \times 10^3 \text{ Btu/hr (2.1 kw)}$$

c) Walls in Earth

(i) Summer Operation

$$q_{s1} = \frac{2.75 \times 10^4}{11.27} = 2.44 \times 10^3 \text{ Btu/hr (0.7 kw)}$$

$$(\Delta t = 30^\circ\text{F})$$

$$q_{s2} = \frac{6.03 \times 10^3}{3.64} = 1.66 \times 10^3 \text{ Btu/hr (0.5 kw)}$$

$$(\Delta t = 25^\circ\text{F})$$

$$\text{Total } q_s = 4.10 \times 10^3 \text{ Btu/hr (1.2 kw)}$$

(ii) Winter Operation

$$q_{w1} = \frac{4.12 \times 10^4}{11.27} = 3.65 \times 10^3 \text{ Btu/hr (1.1 kw)}$$

$$(\Delta t = 45^\circ\text{F})$$

$$q_{w2} = \frac{8.44 \times 10^3}{3.64} = 2.32 \times 10^3 \text{ Btu/hr (0.7 kw)}$$

$$(\Delta t = 35^\circ\text{F})$$

$$\text{Total } q_w = 5.97 \times 10^3 \text{ Btu/hr (1.8 kw)}$$

d) Floor in Earth

$$q_s = \frac{2.41 \times 10^4}{3.14} = 7.68 \times 10^3 \text{ Btu/hr (2.3 kw)}$$

$$(\Delta t = 30^\circ\text{F})$$

$$q_w = \frac{3.62 \times 10^4}{3.14} = 11.52 \times 10^3 \text{ Btu/hr (3.4 kw)}$$

$$(\Delta t = 45^\circ\text{F})$$

e) Total Digester Heat Loss at Mesophilic Operation (95°F - 35°C)

	<u>Winter</u>	<u>Summer</u>
Roof	13970	4460
Walls in Air	7060	3490
Walls in Earth	5970	4100
Floor in Earth	<u>11520</u>	<u>7680</u>
	38520 Btu/hr	19930 Btu/hr
	$q_w = 0.92 \times 10^6 \text{ Btu/day}$	$q_s = 0.48 \times 10^6 \text{ Btu/day}$
	(11.2 kw)	(5.9 kw)

APPENDIX 4

APPENDIX 4

SUMMARY OF DIGESTER PERFORMANCE

	Raw Sludge			Digester Loading lb VS/ft ³ /day kg/m ³ ·d	Reten- tion time Days	Overall			Digested Sludge			Super- natant Liquor % TS
	Feed Rate lgpd (m ³ /d)	% TS	% VS			Vola- tile Solids Reduc- tion %	Gas Prod'n ft ³ /day (m ³ /d)	Specific Gas Prod'n ft ³ /lb (m ³ /kg) VS Destroyed	% TS	% TVS	Vol. Removed lgpd (m ³ /d)	
Elmira Thermo- philic Study												
Phase 1	4000 (18.0)	4.8	63.2	0.08 (1.28)	26	39	9600 (271)	20.2 (1.25)	3.1	50.3	3600 (16)	2.5
Phase 2	7300 (33)	4.8	63.2	0.14 (2.24)	13.3	43	14000 (396)	16.0 (0.99)	2.9	52.2	6600 (29)	2.7
Phase 3	13000 (59)	4.8	63.2	0.20 (3.20)	7.5	37	18700 (528)	16.9 (1.06)	2.9	51.5	12000 (52)	2.9
Waterloo Meso- philic Digester	35600 (161)	4.5	63.8	0.08 (1.28)	23	40	67500 (1910)	16.0 (0.99)	2.8	52.0	31300 (142)	1.6

All results shown are averages. Elmira Phase 4 results are not included due to the nonsteady state nature of that phase.

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